Stockholm Resilience Centre
Research for Governance of Social-Ecological Systems

Stockholm University

Master´s Thesis, 60 credits
Ecosystems, Governance and Globalisation Master´s programme 2008/10, 120 credits

The domino effect

A network analysis of regime shifts drivers and causal pathways

Juan Carlos Rocha

A centre with: SEI Stockholm Environment Institute; The Beijer Institute of Ecological Economics

The domino effect: A network analysis of regime shifts drivers and causal pathways

Paper presented as master thesis in the programme Ecosystems Governance and Globalization at Stockholm University, 18th May 2010.

Juan Carlos Rocha

Stockholm Resilience Centre
Stockholm University
SE 106 91 Stockholm
SWEDEN

e-mail: juancarlosrochag@gmail.com
Mobile: +46 (0) 73 074 7766

ABSTRACT: The purpose of this paper is to perform an exploratory analysis of the causal interactions among global change drivers of regime shifts. Causal loops diagrams were used to collect a set of feedback mechanisms underlying abrupt change dynamics in 11 regime shifts. In order to prioritize drivers and to map out possible causal pathways we used network analysis. Agricultural processes, global warming, biodiversity loss, demographic and economic drivers are the main causes of regime shifts. Based on the analysis of 400 pathways, we intuitively suggest five types of cascading effects between regime shifts. Regime shifts dramatically affect the provision of ecosystem services and might undermine the achievement of the first Millennium Development Goal: reduction of hunger and poverty.

Key words: regime shift, drivers, network analysis, causal pathways

ACKNOWLEDGEMENTS: Members of the Regime Shift Data Base group are gratefully acknowledge for their valuable input and inspiring discussions, especially Oonsie Biggs and Garry Peterson for their supervision. Matteo Giusti, Johanna Mård Karlsson, Susa Niiranen, Christine Hammond and Rolands Sadauskis provided regime shifts cases included in our analysis. Julia Wesely, Kari Stange, Hanna Sterve, Lisen Runsten, Ana Lucía Cardona, Annelie Brand, Megan Meacham, Quentin Helgren and Christian Stein provided great feedback and useful comments on previous version of this manuscript. This work would have not been possible without the support and funding of the Stockholm Resilience Centre. It is dedicated to the memory of María del Carmen Guerrero.

The domino effect: A network analysis of regime shifts drivers and causal pathways

Juan Carlos Rocha

INTRODUCTION

Over the past 50 years humans have changed ecosystems faster and more extensively than in any other comparable period in the past. In comparison with the pre-industrial era, human population has grown six-fold, the world's economy 50-fold and energy consumption 40-fold (Steffen et al. 2007). While few global change drivers like deforestation or nutrient inputs have been largely studied (e.g. Carpenter et al. 1999, Geist and Lambin 2002), our understanding on how global change drivers interact is rather poor. Interactions between drivers often result in abrupt, non-linear changes that affect system function and outputs, which are also known as regime shifts (Scheffer 2009). Regime shifts can dramatically undermine the ecosystem services human societies rely upon. Moreover, regime shifts can exacerbate global change drivers as well, generating in turn signals that travel in the causal chain like domino effect, possibly encountering other regime shifts in its pathway. Here we study the main causes and consequences of regime shifts by looking at drivers interactions in the causal pathways.

Scheffer (2009) defines regime shifts as "a relatively sharp change from one regime to a contrasting one, where a regime is a dynamic 'state' of a system with its characteristics stochastic fluctuations and/or cycles". Although there is no agreement on one definition, the slight differences among definitions reside on the meaning of stability -the measure of what a regime is- and the meaning of abruptness. At the end it is a matter of scale. In order to apply the concept to a particular problem, one has to limit its range of dynamics by fixing analytical categories such time and space scales, range of variations and exogenous / endogenous processes. For example, while for oceanographers a regime must last for at least decades and should include climate variability as a driver, for marine biologists it is more accepted regimes of only five years and could be induced only by population dynamics. Appendix 1 summarizes the theoretical background on regime shifts and collects some common definitions and their modifications used in ecology.

Central to managing regime shifts is understanding the drivers of change are and how they can be managed to keep the system in a safe operating space for humanity. The Millenium Ecosystem Assessment (MA) reviews global change drivers of ecosystem change and human well being (Ecosystem Assessment 2005). They define a driver as "any natural or human-induced factor that directly or indirectly causes a change in an ecosystem. A direct driver unequivocally influences ecosystem processes. An indirect driver operates more diffusely, by altering one or more direct drivers" (Nelson 2005). The MA identified as the main direct drivers: climate change, nutrient pollution, land conversion, resource overexploitation, and invasive species and diseases. The key indirect drivers were demographics, economics, sociopolitical, scientific and technological, and cultural and religious (Nelson 2005). Likewise, Folke *et al.* (2004) suggest that the main anthropogenic drivers of change in social-ecological systems are resources exploitation, pollution, land-use change, climatic impacts and the alteration of disturbance regimes.

Global change drivers are more than a set of causes and consequences. Rather, they form patterns of interactions that can trigger regime shifts from the micro or the macro level dynamics (e.g. overfishing and global warming respectively). We believe that some regime shifts that apparently are not that important at the local or regional scale, when aggregated could actually precipitate major changes in other regime shifts. This phenomenon nested in scale could explain emergent patterns. For example, Jackson *et al.* (2001) and Diaz & Rosenberg (2008) separately report a global syndrome in coastal ecosystems where hypoxia, fisheries collapse and jelly fish outbreaks seems to be closely related. These possible links are important to managers, who are concerned with what is manageable and what is not at their scale of action. The analysis of cross-scale interactions could help to clarify management practices in causality clusters, to identify factors that are manageable and not manageable, even if the regime shifts dynamics occur at other scale in time and space. Understanding cascading effects among regime shifts would help to highlight key drivers on which to focus policy action and suggest key areas for future research.

Regime shifts can dramatically affect the flow of ecosystem services that human societies rely upon. Moreover, changes in ecosystem services might alter other drivers of system change (Nelson 2005). For this reason it is important to understand the mechanisms underlying regime shifts, their impacts on social-ecological systems, as well as their implications for human well-being. Better understanding of regime shifts dynamics could help to anticipate them, to avoid undesirable ones as well as enhancing beneficial regime shifts for society.

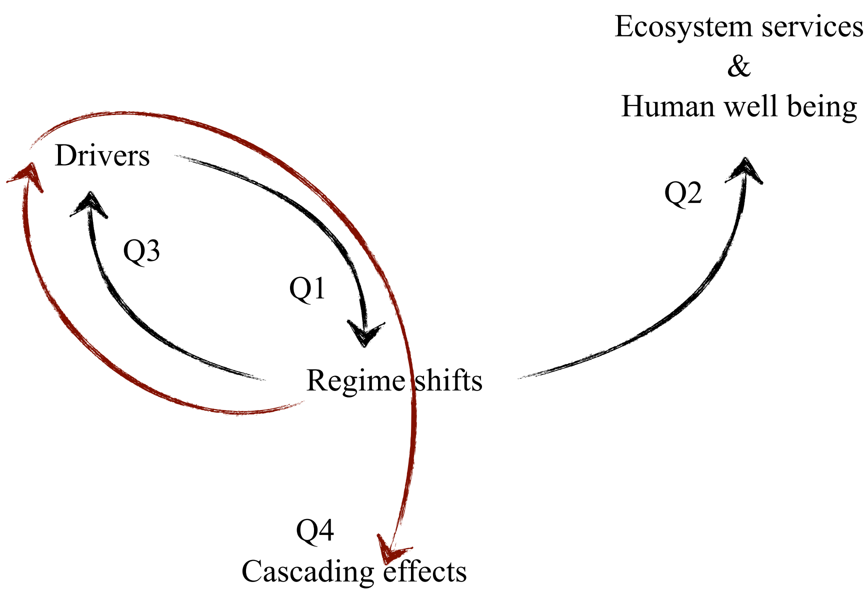


Figure 1. Each arrow represents one of our research questions.

The main objective of this paper is to perform an exploratory analysis of the causal interactions among global change drivers of regime shifts. We investigated four major questions: Q1. What are the major global change drivers of regime shifts? Q2. What are the impacts of regime shifts on ecosystems and ecosystem services?, Q3. What are the impacts of regime shifts on global change drivers, and Q4. What are the possible cascading effects of regime shifts and its drivers? (Figure 1). A parallel objective is developing new methodological approaches to tackle the issue of causality in regime shifts. We limit our analysis to abrupt changes that matter to people both in terms of drivers and consequences. More specifically, we focus on abrupt change that leads to different configuration of *ecosystem services,* namely the benefits people obtain from ecosystems (Millennium Ecosystem Assessment 2005); as well as on managerial options to keep systems in desirable regimes and avoid undesirable regimes.

METHODS

Data sources

The analyses in this paper are based on regime shifts recorded in the pilot version of the Regime Shifts Database[1] (RSDB). The RSDB provides a compilation of different types of regime shifts, based on assessment and synthesis of the literature. For each regime shift type, the following information is recorded: *i)* a description of the alternative regimes and reinforcing feedbacks, *ii)* the drivers that precipitate the regime shift, *iii)* impacts on ecosystem services and human well-being, and *iv)* management options. Based on the conceptual framework of the MA (2005), each regime shift was classified by ecosystem type, land use, impacts on ecosystem services and ecosystem processes. For more detailed information see the data capture template in Appendix 2. To ensure data quality, the description of each regime shift compiled from the literature was reviewed by an expert prior to uploading it to the database.

A potential list of regime shifts was developed based on the Thresholds Database (Resilience Alliance & Santa Fe Institute 2004) and updated with literature survey. Only examples fulfilling the following three criteria were included in the RSDB. First, the literature must provide some evidence of the mechanistic dynamics underlying the regime shift. Second, we only included regime shifts that matter to people, i.e., that have significant impacts on ecosystem services. Third, we prioritized regime shifts over threshold-like responses. This criterion therefore required some evidence that the regime shift is hard to reverse, implying the presence of hysteresis. Regime shifts with unknown reversibility were also included.

The pilot version of the RSDB contains 11 types of regime shifts, the basis for this analysis (Table 1). This list corresponded to the best documented and established cases based on a literature survey. Therefore, it represents the most researched regime shifts and reflects academic interest, funding priorities and data availability. It is therefore a biased sample. A summary of each regime shifts is given in Appendix 3.

Table 1. Regime shifts contained in the pilot RSDB and analyzed in this paper. Four different attributes are summarized: *i)* biome in which it occurs, *ii)* confidence about the existence of the regime shift, ranked as well *established, contested* or *speculative*; *iii)* confidence about the mechanism, given as *speculative, contested* or *well established*; and *iv)* reversibility, given as irreversible (*I*), hysteretic (*H*), readily reversible (*R*) or unknown (*U*). Note that reversibility may vary in different contexts.

[1] www.regimeshifts.org, an initiative of the Stockholm Resilience Centre, Stockholm University, Sweden.

Policy relevant regime shifts	Biome	Evidence	Mechanism	Reversibility
Coral to algae dominance	Marine	Established	Established	H
Coral bleaching	Marine	Established	Established	H
Kelp forest collapse	Marine	Established	Established	H, R
Bivalve collapse	Marine	Established	Established	H
Hypoxia	Marine, Fresh water	Established	Established	H, R
Fisheries collapse	Marine, Fresh water	Contested	Contested	U
Fresh water eutrophication	Fresh water	Established	Established	H, I, R
Soil salinization	Drylands	Established	Established	H, I
Bush encroachment	Savannas	Contested	Contested	H
Steppe - tundra transition	Tundra	Established	Contested	I
Tundra to forest transition	Tundra	Speculative	Established	I

Constructing causal-loop diagrams

A set of regime shift causal-loop diagrams (CLD) was developed following the protocol described by Sterman (2000), using Vensim PLE (Ventana Systems 2010). CLD is a technique to map out the feedback loop structure of a system. CLD consist of variables connected by arrows denoting causal influence between them, where a positive link means direct proportional relationship and negative link means inverse proportional relationship. Link polarities describe the structure of the system by forming loops that can be reinforcing feedbacks where the aggregate polarity is positive, or balancing feedbacks when negative (Sterman 2000). These diagrams helped us to better visualize information, delay dynamics, and identify possible drivers interactions.

We intend to provide a set of feedback mechanisms, drivers and triggers underlying abrupt change dynamics. For our purpose, drivers are fast processes that change the dynamics of the system (function) or slow processes that promote change on the structure of the system. Thus, a slow process can turn on and off feedback loops that lead to different dynamics on the same system. A trigger is also a driver, but in a contextual case. A trigger is related to the last perturbation received before a system undergoes a regime shift.

Our approach is not case study based. We take a step back and try to generalize when abrupt change happens, which systems are prone and what can be the underlying mechanisms independently of the case specific context. To clarify our approach we use the example of coral reefs. We know corals have been resilient to different stressors in time (e.g.. hurricanes, diseases, outbreaks, changes in fishes communities, etc) but under *certain conditions* they can shift to an algae dominated state (Bellwood et al. 2004). These certain conditions are the drivers, slow variables or parameters of the system. For the coral example they could be: turbidity, sea surface temperature (SST), low tides, nutrient pulses, fishing pressure, diseases, and the lost of herbivores control over algae growth as shown in Figure 2. These are generic features. While in a case specific examples the configuration of such conditions are definitely different. Shifts in coral to algae dominance have occurred in the Caribbean triggered by the lost of herbivory control (an outbreak which diminish up to 10% the population of sea urchins) whereas in Australia such shifts have been triggered by coral bleaching, an event related with water temperature. The interaction among drivers is what make the difference among study cases. In order to make an informed generalization, we are interested in collecting all the drivers and feedback processes that explain in a generic way particular regime shifts.

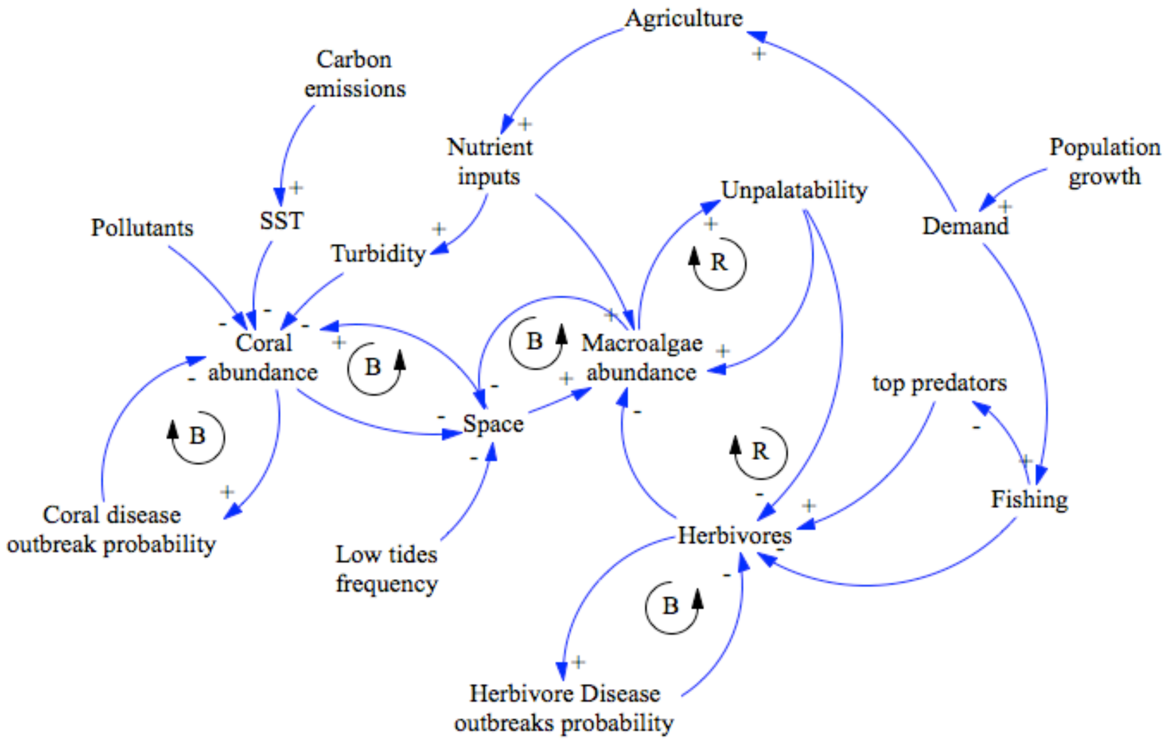


Figure 2. Causal loop diagram for the coral reef transitions example. Reinforcing feedbacks are marked by R, and balancing feedbacks with B.

Identifying drivers of regime shifts

Based on the CLD, we identified the drivers of change for each regime shift. For the coral example, the drivers of change are sedimentation (turbidity), change in temperature, tides frequency, nitrogen and phosphorous fertilization, fishing, diseases and loss of herbivores. The variables in each causal-loop diagram are very specific to each regime shift type. To ease comparison between them, the drivers were grouped into broader categories in such a way that each driver is general enough to be applied to any CLD, but specific enough not to overlap with other categories (Table 2). Our classification of global change drivers is similar to the classification frameworks proposed by Nelson (2005) in the MA, and Folke *et al.* (2004), but slightly different from the drivers initially proposed in the RSDB data capture template.

Table 2. Drivers categorization. On the top-row the global change drivers, some of them already proposed in the MA (Nelson 2005). Regime shifts drivers correspond to the sub-categories developed to suit the different causal-loop diagrams describing change for each regime shift.

Global change drivers	Resource exploitation	Pollution	Land use change	Climate impacts	Alteration of frequency disturbance	Alteration of biodiversity	Demographics	Economics
Regime shift drivers	Grazing	Nitrogen / Phosphorous fertilization	Deforestation	Change in temperature	Erosion	Introduced animals	Human population growth	Global movement of resources
	Soil exploitation (agriculture)	Heavy metals and persistent organic pollutant	Fragmentation	Change in CO_2 in the atmosphere	Modified fire regimes	Introduced plants	Consumption patterns	Perverse incentives
	Logging	Sewage	Urbanization	Change in CO_2 in the oceans	Irrigation	Loss of herbivores		Subsidies
	Hunting		Conversion to crops (Agriculture)	Change in droughts and floods	Sedimentation	Loss of predators		Tragedy of the commons
	Dry out aquifers		Impoundment	Water stratification	Tides frequency	Loss of organic soils		Demand for food and fiber
	Fishing		Infrastructure (roads, elect. grids)	Upwellings	Flushing			Poverty
	Irrigation		Vegetation patters change through grazing		Technology			

Network analysis

In order to prioritize drivers and to map out possible causal pathways between regime shifts we used network analysis. A network is a collection of nodes or vertices, some of them connected by links or edges. For our network, regime shifts and their drivers are nodes. Based on CLD, an adjacency matrix of linkages between regime shifts and drivers was built taking into consideration directionality. Each link represents causality between drivers and/or regime shifts. Polarity -positive or negative relationships in the CLD- were excluded in the network representation since it is expected to vary from case to case. Our analysis was performed in R (R Development Core Team 2009) using the following software packages: *network* (Butts et al. 2008), *statnet* (Handcock et al. 2003), *sna* - social network analysis (Butts 2009), and *igraph* (Csardi and Nepusz 2006).

The importance of the drivers was captured in different ways. First, we looked at the frequency at which they are reported in the RSDB. Then, we used network centrality, a family of node-level properties, to capture the structural importance of a node given its position and connections on the network (Borgatti et al. 2009). Centrality can be decomposed into different measurements, as summarized in Table 3. Each measurement is further explained in the light of the question it attempts to answer.

Table 3. Summary of centrality properties used in the network analysis.

Centrality	Definition	Equation	Questions
Degree	The number of nodes to which a node is adjacent (Scott 2000)	$x_i = \sum_j a_{ij}$	1, 3
Betweenness	The extent to which a node lies ‘between’ other nodes in a graph (Scott 2000)	$x_i = \sum_{\substack{i \neq j, i \neq k \\ j \neq k}} \frac{\sigma_{jk}(i)}{\sigma_{jk}}$	1

Centrality	Definition	Equation	Questions
Eigenvector	A node is important if it is connected directly or indirectly to other nodes that are in turn important (Allesina and Pascual 2009)	$x = \frac{1}{\lambda} Ax$, and $x_i = \mu \sum_{j=1}^{n} a_{ij} x_j$	1
Closeness	The number or proportion of points to which a node is connected (Scott 2000)	$C_C(v) = \frac{\sum_{i:i \neq v} \frac{1}{d(v,i)}}{\lvert V(G) \rvert - 1}$	1, 3

Q1. What are the major global change drivers of regime shifts?

Local centrality or degree is the number of nodes to which a node is adjacent (Scott 2000). We used degree to identify which drivers are more connected, hence which ones are involved in more causal pathways. Degree is a measurement of local centrality because it only counts adjacent edges. Given our network is directed, two forms of degree centrality arise: in-degree and out-degree. If you imagine a series of causal pathways leading to a particular regime shift, the immediate drivers are those with one degree of separation from the regime shift -given an out degree setting- as shown in Figure 3. Likewise, immediate consequences are drivers with one degree of separation in an in-degree setting. Immediate drivers are like symptoms and they might be relevant for monitoring programs.

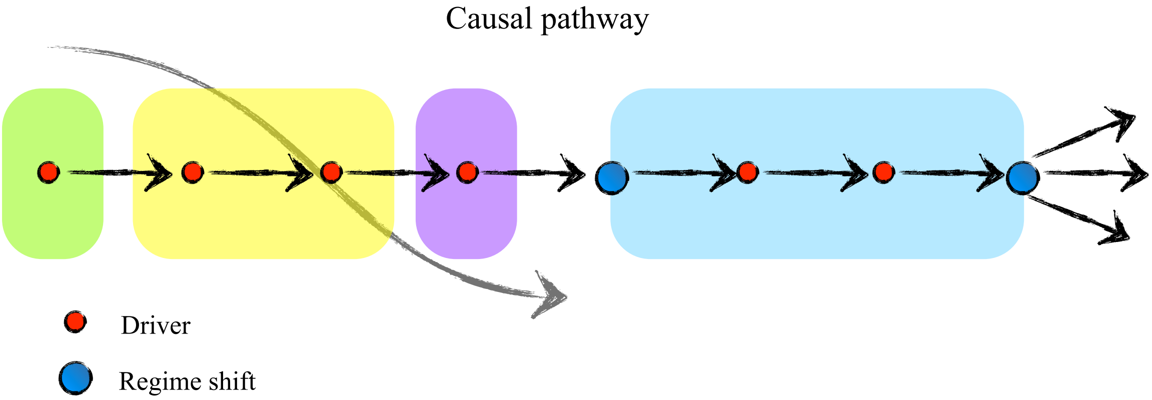


Figure 3. Causal pathways. Each color highlight different set of drivers given its importance. In purple immediate causes of regime shifts. In the yellow area we expect to find drivers with high eigenvector and betweenness centrality, given they are the most connected with other pathways. In the green area the causal roots. Cascading effects will be found in the blue area.

Betweenness measures the extent to which a node lies between other nodes. In other words, the extent to which a node can play as intersection of several pathways, with potential influence over others nodes (Scott 2000). In contrast to degree, it capture the proportion of paths that would be broken if a node would not exist -or if a driver is successfully managed-, independently of its local neighborhood. In addition, eigenvector centrality recalculates the importance of a node given the importance of the nodes to which it is connected. Since both measurements are expected to correlate, a linear model was fitted. Drivers with high betweenness and eigenvector centrality would be important for management since they connect different pathways and might cause several regime shifts.

Global centrality or closeness is the average distance to all other nodes in the graph. Far distance nodes in the causal pathway are the roots of the problem, identified by using the inverse of closeness. As our network is directed, out-closeness and in-closeness were calculated. While nodes with high out-closeness are the farthest causes, nodes with high in-closeness are the farthest consequences of regime shifts. Both measurements were fitted into a linear model. It can be difficult or even impossible to establish relationships between distant drivers and regime shifts. Nevertheless, they are key in long term management strategies because they are at the origin of different causal pathways.

Q2. What are the impacts of regime shifts on ecosystems and ecosystem services?

Based on the RSDB, we looked at the frequency at which ecosystem services were reported in each case. We included provisioning, regulatory and cultural services in our analysis. Supporting services were handled separately as ecosystem processes and biodiversity in our data capture template, so we did here. In addition, we looked at the ecosystems most affected by regime shifts reported in the RSDB.

Q3. What are the impacts of regime shifts on global change drivers?

Spillover effects occur when a particular regime shift amplifies other regime shift drivers. Such effects were assessed by looking at in-degree linkages from regime shifts nodes on the network. By doing so, we got a rough idea of immediate consequences -one edge of separation- of regime shifts on its own or other regime shifts' drivers. In addition, we use in-degree closeness as indicator to capture far reaching consequences in the causal pathways.

Q4. What are the possible cascading effects of regime shifts and its drivers?

Based on the spillover effects, we assessed possible pathways between regime shifts taking directionality into account. First we calculated the diameter of the regime shifts network, namely the longest possible pathway between two nodes. Then, all shortest pathways between two regime shifts were calculated using Breadth-Fist Search (Easley and Kleinberg 2010). Each pathway was manually checked in order to find possible incongruent data. Although this is time consuming, this step is necessary given the risk of inferring wrong pathways. Because the matrix adjacency was built based on literature review regarding causes of regime shifts rather than its consequences, such risk is high. The plausibility of pathways found was confirmed with literature review.

RESULTS

This section summarizes the major findings structured by the four questions that guide our study.

Q1. What are the major global change drivers of regime shifts?

Figure 4 outlines the main drivers of change leading to regime shifts and land uses under which they are likely to appear based on the RSDB template. *Global climate change* related variables contribute to the causation of 8 out of the 11 regime shifts studied. *Harvest and resource consumption* (6 regime shifts) and *external inputs* (7 regime shifts) cause about two thirds of regime shifts, accounting for the second most important set of causes; while *infrastructure and development* (0) is the less important driver. *Fisheries* (6 regime shifts) is the most reported land use where regime shifts happen, followed by *conservation* (5 regime shifts) and *large scale commercial crops cultivation* (5 regime shifts)*;* while the less reported land uses are *timber production* (0) and *small scale subsistence crops cultivation* (0).

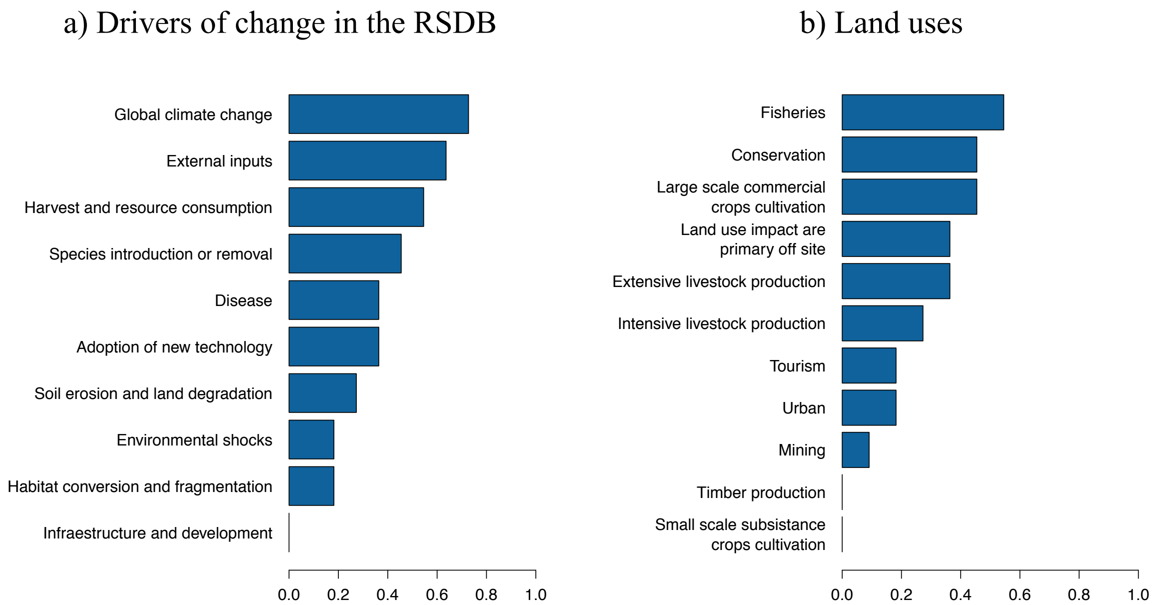


Figure 4. (a) Main drivers of change leading to regime shifts, and (b) frequency of regime shifts under different land uses. Categories reflect those in the data capture template. Relative frequency given as a fraction where 1 would be presence in all regime shifts (n=11).

Immediate causes of regime shifts were surveyed by looking at links of one degree distance in an out-degree graph (Figure 5). Note that we use here the disaggregated categories from Table 2. The most important immediate cause of regime shifts is *sedimentation,* affecting 7 regime shifts. V*egetation pattern change through grazing, nitrogen and phosphorous fertilization* and *fishing* are the cause of 6 regime shifts; followed by *loss of herbivores* and *loss of predators* which are the cause of 5 regime shifts. Whereas *sedimentation, nitrogen and phosphorous fertilization* and *fishing* are the most common drivers for regime shifts in aquatic environments, *vegetation pattern change through grazing* is the most common for terrestrial ecosystems. More than half of the immediate cause drivers are linked with only one regime shift.

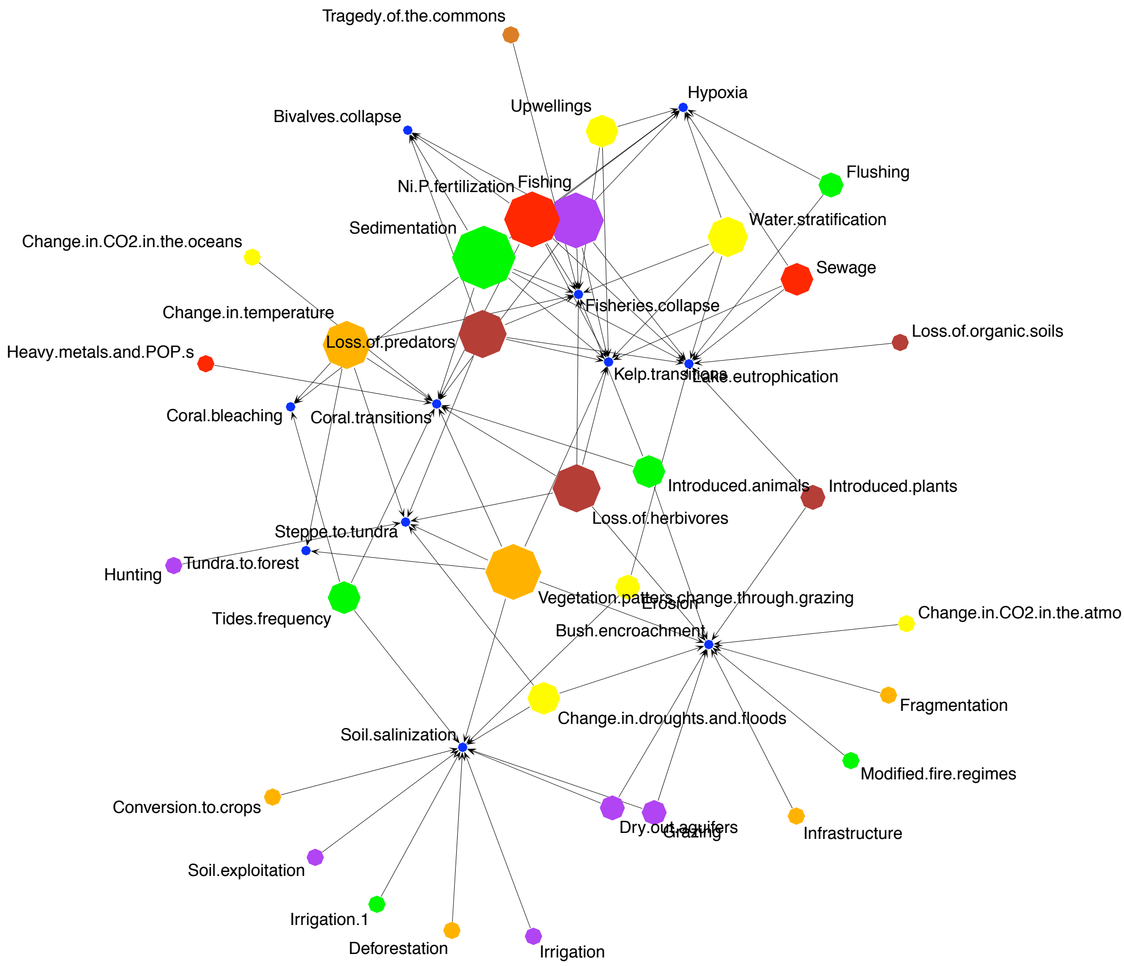


Figure 5. Direct drivers of regime shifts. Node size correspond to out-degree or the number of causation links to regime shifts nodes (in blue). Each color correspond to global change drivers categories in Table 2: Resource exploitation (purple), pollution (red), land use change (orange), climate impacts (yellow), alteration of frequency disturbance (green), alteration of biodiversity (brown), demographics (grey) and economics (chocolate).

When considering all drivers and regime shifts, their relative importance of different nodes changes as shown in Figures 6a and 6b, where degree and betweenness centrality serve as indicators. Sorted by degree centrality, the most important driver is *conversion to crops* which is connected to other 36 nodes both in and out degree. It is followed by *soil exploitation* (26 links) and by *loss of predators* (25 links). From the sizes distribution respect to drivers categories (highlighted by colors), we cannot infer which global change driver is more important (headers categories in Table 2). However, note that the regime shifts in blue can be as central as other drivers, indicating that they are nodes in the middle of pathways rather than end points. This suggest that domino effects between regime shifts are actually likely to happen. In contrast, betweenness offer a measure of importance given a general rather than local context. While *conversion to crops* is consistent as the most important, it is followed in the rank by *tragedy of the commons, fisheries collapse* and *change in temperature.* These drivers are connecting the major number of possible pathways between all nodes in the network. Interestingly, drivers under the category *economics* and regime shifts gain importance with betweenness.

a) Degree centrality

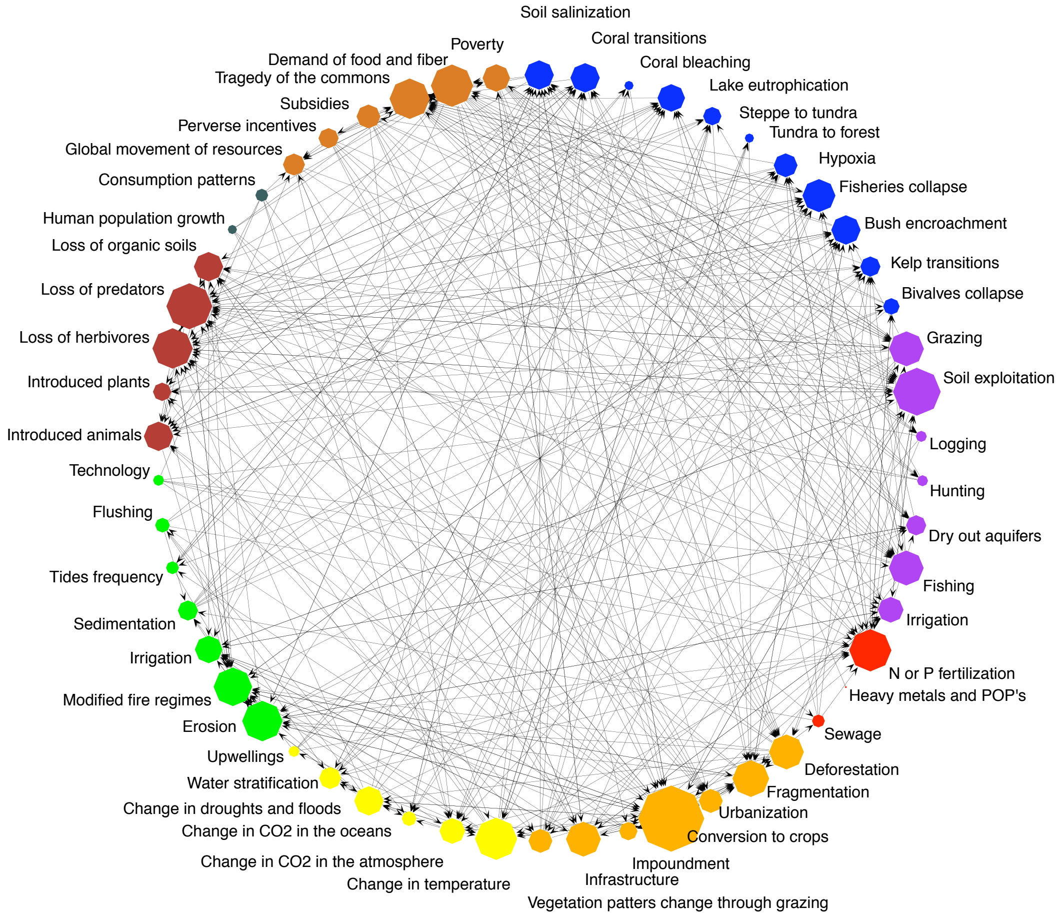


Figure 6a. Degree centrality. Networks graph is organized as circle to facilitate reading. Node size is rescaled and correspond degree score. Regime shifts nodes are in blue. For drivers, each color corresponds to categories in Table 2: Resource exploitation (purple), pollution (red), land use change (orange), climate impacts (yellow), alteration of frequency disturbance (green), alteration of biodiversity (brown), demographics (grey) and economics (chocolate)

b) Betweenness centrality

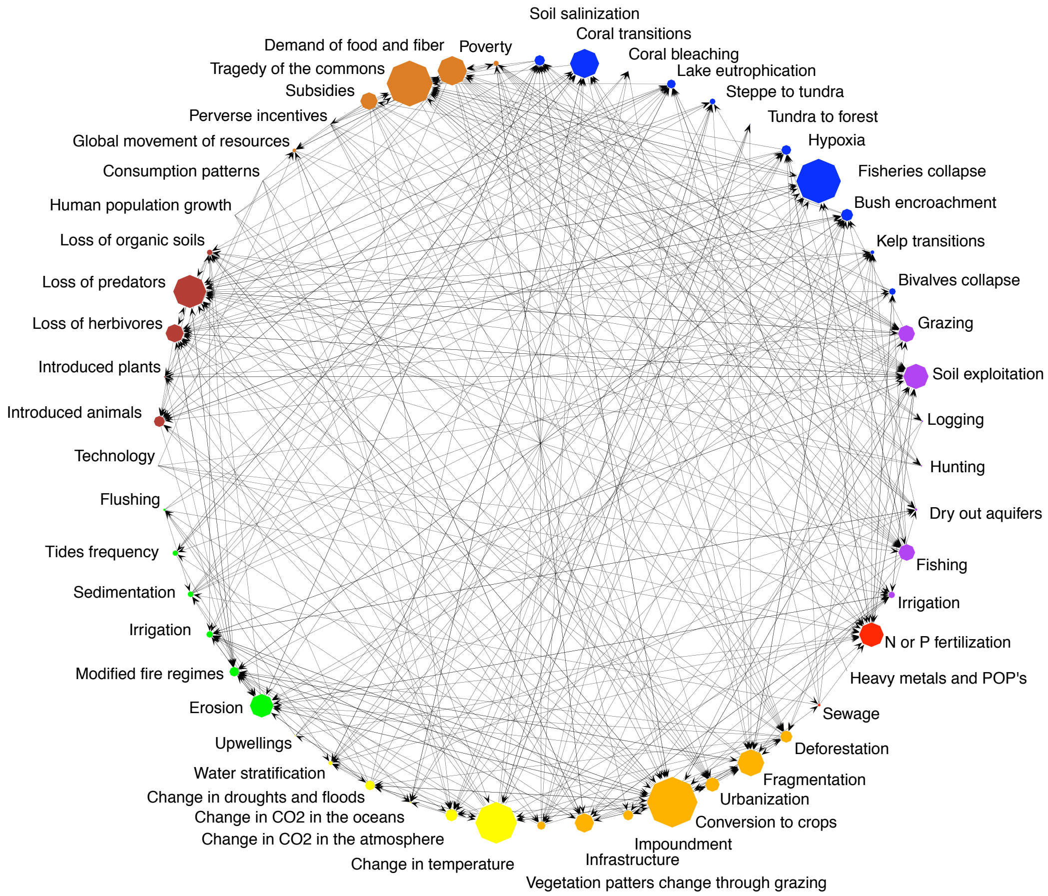
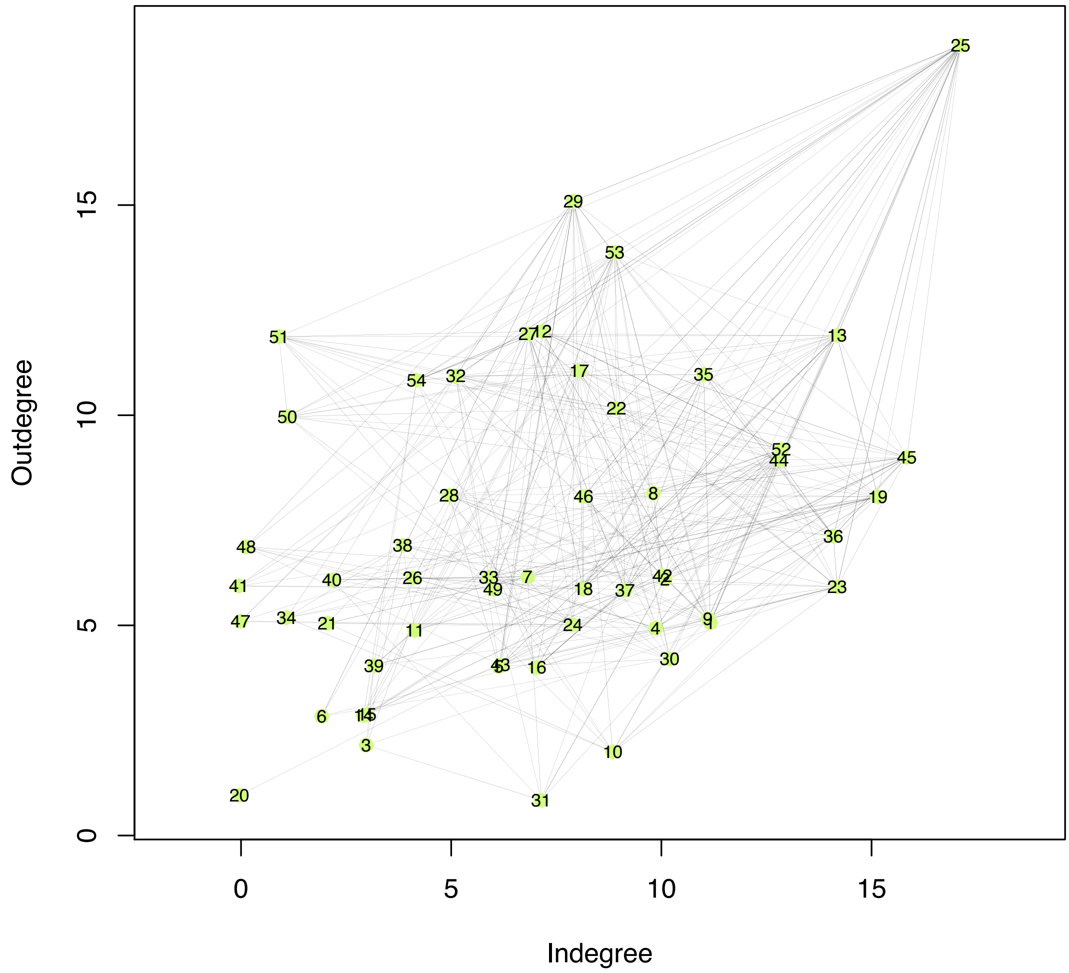


Figure 6b. Betweenness centrality. Networks graph is organized as circle to facilitate reading. Node size is rescaled and corresponds betweenness score. Regime shifts nodes are in blue. For drivers, each color correspond to categories in Table 2: Resource exploitation (purple), pollution (red), land use change (orange), climate impacts (yellow), alteration of frequency disturbance (green), alteration of biodiversity (brown), demographics (grey) and economics (chocolate).

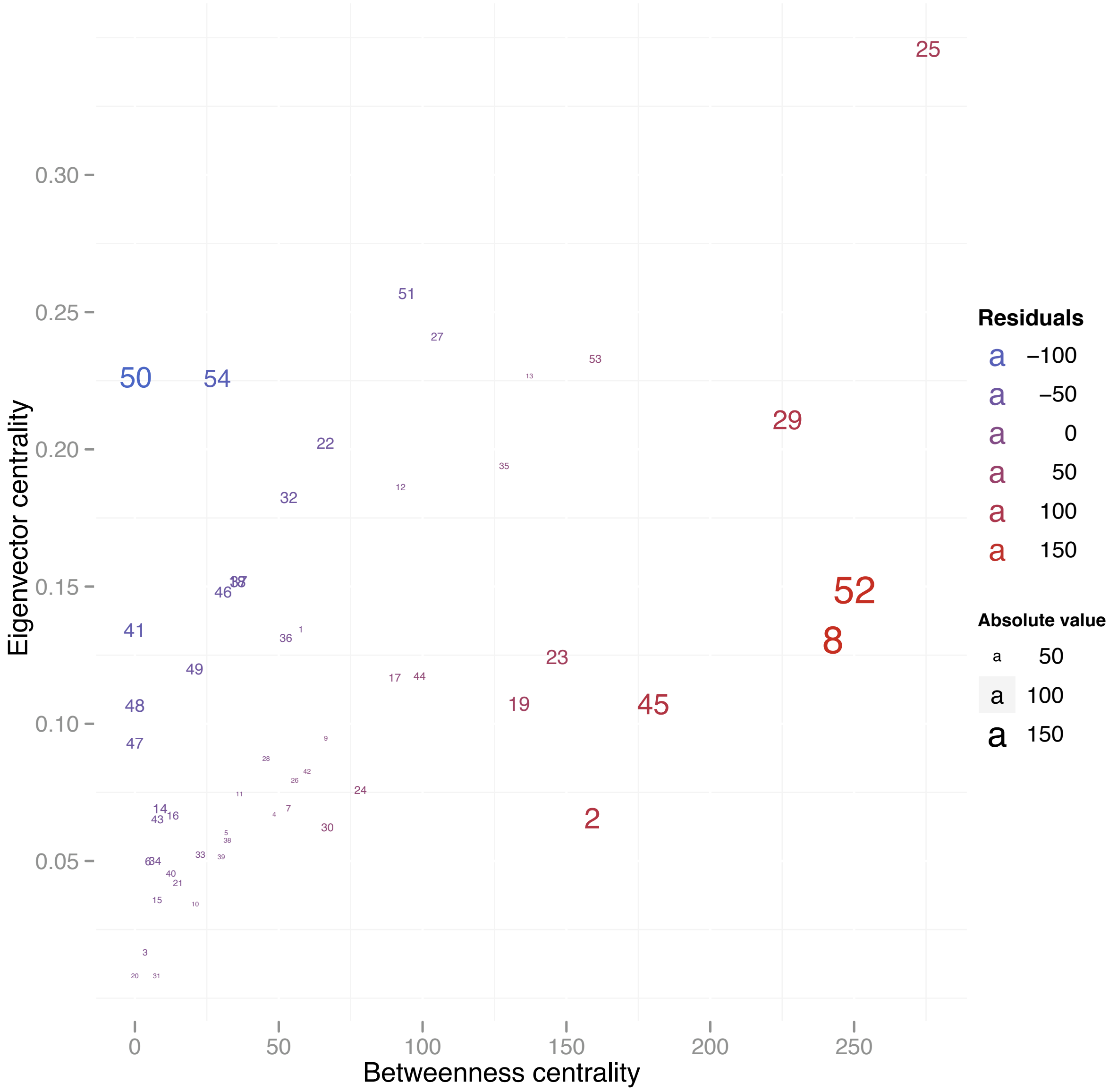
Given that the graph is directed, drivers with more out-degree links are involved in more pathways as causes. Once again, *conversion to crops* is the first with 19 links, followed by *change in temperature* (15 links) and by *demand for food and fiber* (14 links), as revealed in Figure 7a. In contrast, *Heavy metals and persistent organic pollutants (POP's)* is, according with degree centrality, the least important driver, with only one connection to the *coral transition*s regime shift.

Both betweenness and eigenvector centrality measure similar properties of the nodes. For this reason a linear model was fitted. In Figure 7b, the residuals of the model are rescaled in nodes size and color, thus red, big nodes representing high betweenness, and blue, big nodes high eigenvector centrality. *Conversion to crops* is clearly an outlier in the plot, clearly becoming the most important driver for both properties. The *tragedy of the commons, fisheries collapse* and *changes in temperature* follow the rank by betweenness, while *perverse incentives, poverty* and *subsidies* lead the list by eigenvector centrality. For both measurements, *coral bleaching, change in temperature* and *change in* CO_2 *in the oceans* are the least important drivers.



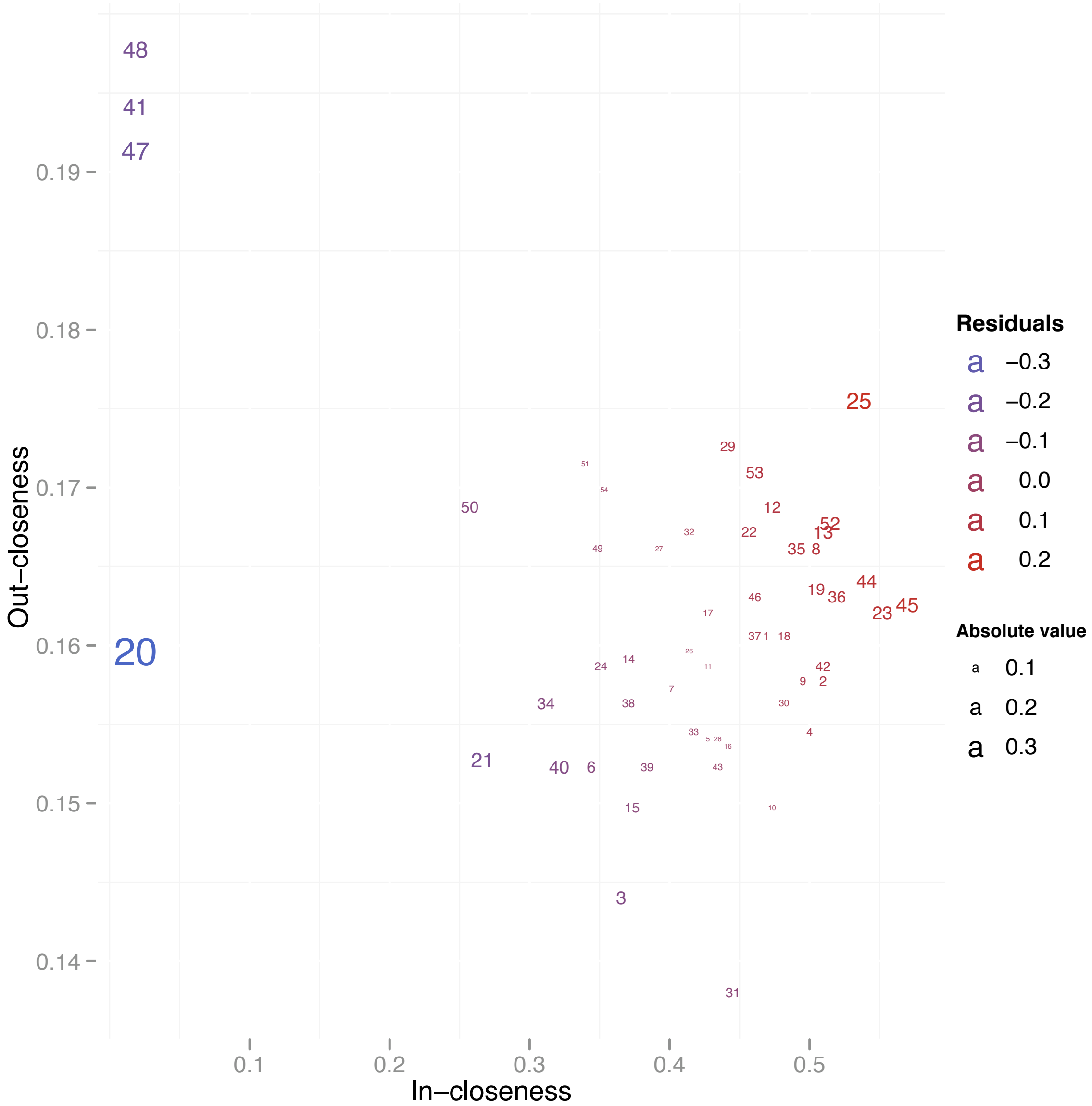
	Regime shifts	13	Soil exploitation	27	Infrastructure	41	Technology
1	Soil salinization	14	Logging	28	Vegetation patters change through grazing	42	Introduced animals
2	Coral transitions	15	Hunting	29	Change in temperature	43	Introduced plants
3	Coral bleaching	16	Dry out aquifers	30	Change in CO2 in the atmosphere	44	Loss of herbivores
4	Lake eutrophication	17	Fishing	31	Change in CO2 in the oceans	45	Loss of predators
5	Steppe to tundra	18	Irrigation	32	Change in droughts and floods	46	Loss of organic soils
6	Tundra to forest	19	N or P fertilization	33	Water stratification	47	Human population growth
7	Hypoxia	20	Heavy metals and POP's	34	Upwellings	48	Consumption patterns
8	Fisheries collapse	21	Sewage	35	Erosion	49	Global movement of resources
9	Bush encroachment	22	Deforestation	36	Modified fire regimes	50	Perverse incentives
10	Kelp transitions	23	Fragmentation	37	Irrigation	51	Subsidies
11	Bivalves collapse	24	Urbanization	38	Sedimentation	52	Tragedy of the commons
	Drivers	25	Conversion to crops	39	Tides frequency	53	Demand of food and fiber
12	Grazing	26	Impoundment	40	Flushing	54	Poverty

Figure 7a. Centrality of the regime shifts network. The network plotted by degree centrality.



	Regime shifts	13	Soil exploitation	27	Infrastructure	41	Technology
1	Soil salinization	14	Logging	28	Vegetation patters change through grazing	42	Introduced animals
2	Coral transitions	15	Hunting	29	Change in temperature	43	Introduced plants
3	Coral bleaching	16	Dry out aquifers	30	Change in CO2 in the atmosphere	44	Loss of herbivores
4	Lake eutrophication	17	Fishing	31	Change in CO2 in the oceans	45	Loss of predators
5	Steppe to tundra	18	Irrigation	32	Change in droughts and floods	46	Loss of organic soils
6	Tundra to forest	19	N or P fertilization	33	Water stratification	47	Human population growth
7	Hypoxia	20	Heavy metals and POP's	34	Upwellings	48	Consumption patterns
8	Fisheries collapse	21	Sewage	35	Erosion	49	Global movement of resources
9	Bush encroachment	22	Deforestation	36	Modified fire regimes	50	Perverse incentives
10	Kelp transitions	23	Fragmentation	37	Irrigation	51	Subsidies
11	Bivalves collapse	24	Urbanization	38	Sedimentation	52	Tragedy of the commons
	Drivers	25	Conversion to crops	39	Tides frequency	53	Demand of food and fiber
12	Grazing	26	Impoundment	40	Flushing	54	Poverty

Figure 7b. Centrality of the regime shifts network. A linear model of the positive correlation among betweenness and eigenvector centrality. The residuals are highlighted by size and color depending on the respective axes.



	Regime shifts	13	Soil exploitation	27	Infrastructure	41	Technology
1	Soil salinization	14	Logging	28	Vegetation patters change through grazing	42	Introduced animals
2	Coral transitions	15	Hunting	29	Change in temperature	43	Introduced plants
3	Coral bleaching	16	Dry out aquifers	30	Change in CO2 in the atmosphere	44	Loss of herbivores
4	Lake eutrophication	17	Fishing	31	Change in CO2 in the oceans	45	Loss of predators
5	Steppe to tundra	18	Irrigation	32	Change in droughts and floods	46	Loss of organic soils
6	Tundra to forest	19	N or P fertilization	33	Water stratification	47	Human population growth
7	Hypoxia	20	Heavy metals and POP's	34	Upwellings	48	Consumption patterns
8	Fisheries collapse	21	Sewage	35	Erosion	49	Global movement of resources
9	Bush encroachment	22	Deforestation	36	Modified fire regimes	50	Perverse incentives
10	Kelp transitions	23	Fragmentation	37	Irrigation	51	Subsidies
11	Bivalves collapse	24	Urbanization	38	Sedimentation	52	Tragedy of the commons
	Drivers	25	Conversion to crops	39	Tides frequency	53	Demand of food and fiber
12	Grazing	26	Impoundment	40	Flushing	54	Poverty

Figure 7c. Centrality of the regime shifts network.. A linear model of the negative correlation between in and out closeness measurements. The residuals are highlighted by size and color depending on the respective axes.

We calculated the inverse of closeness in order to give higher values to further nodes in the causal pathways. Since the network is directed, out-closeness and in-closeness were calculated and a similar linear model was fitted (Figure 7c). Nodes with outstanding values of out-closeness are the furthest causes. Thus, *consumption patterns, technology* and *human population growth* are the top three of the list. We will be back to in-closeness and in-degree centrality regarding our third question.

Q2. What are the impacts of regime shifts on ecosystems and ecosystem services?

Biodiversity is by far the most common service affected in more than 90% of cases as shown in Figure 8. The most affected ecosystem processes are *primary production, nutrient cycling* and *water recycling. Marine and coastal* ecosystems leads the list of most affected ecosystems (6 regime shifts), followed by *freshwater lakes and rivers* (4 regime shifts).

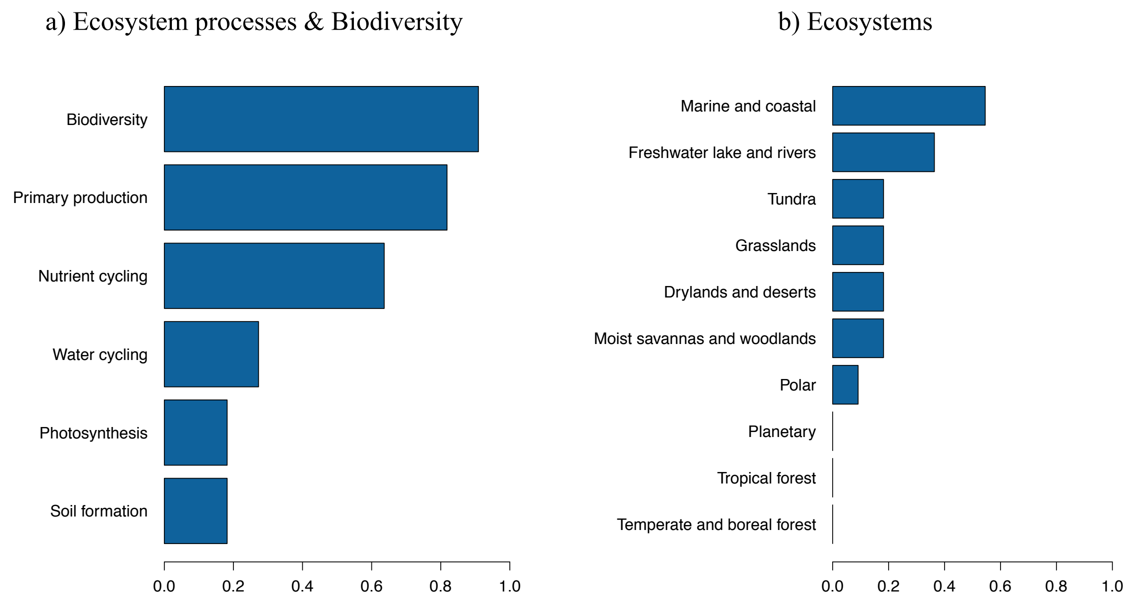


Figure 8. Impacts of regime shifts in ecosystems. a) Ecosystem functions (supporting services) most affected, and b) Types of ecosystems most affected. Relative frequency given as a fraction where 1 would be presence in all regime shifts (n=11).

Fisheries leads the list of the provisioning services most affected by 7 regime shifts, followed by *wild animals and plant foods* (5)(Figure 8). *Water purification* (6) is the regulating service most affected, followed by *climate regulation* (3) and *regulation of soil erosion* (3). *Recreation* and *aesthetic values* (8) are at the top of the cultural services. The most frequent impacts on human well being are *livelihoods and economic activity* and *food and nutrition*, which were affected by all regime shifts in our sample.

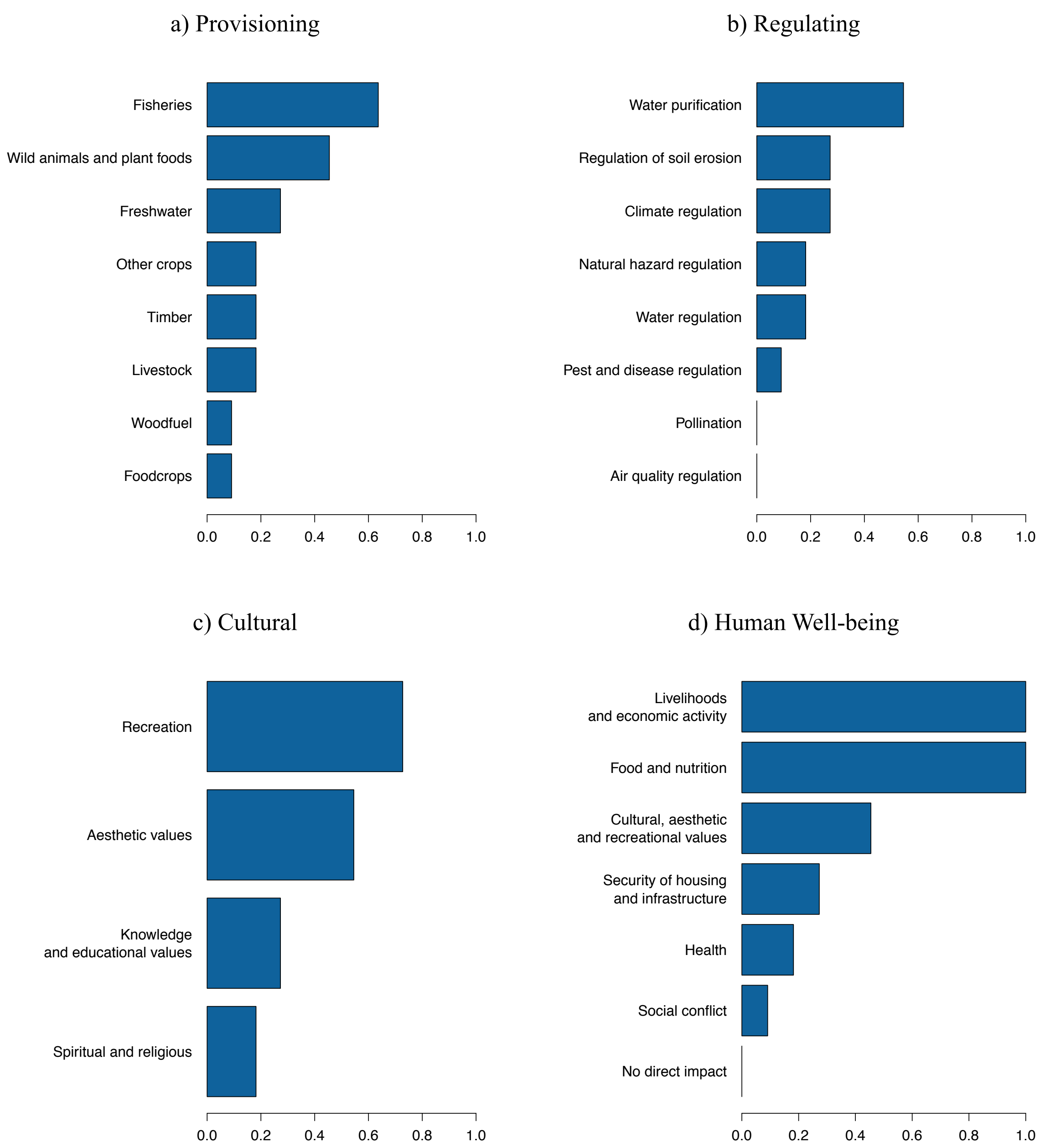


Figure 8. Impacts of regime shifts on ecosystem services and human well being. Relative frequency given as a fraction where 1 would be presence in all regime shifts (n=11).

Q3. What are the impacts of regime shifts on global change drivers?

Nodes with in-degree links coming from other regime shifts are immediate consequences spillover effects of those regime shifts (Figure 9). *Tragedy of the commons* is the most exacerbated driver by other regime shifts with 8 links as immediate consequences, followed by *fragmentation* which is reinforced by 6 regime shifts, and *loss of predators, change in CO_2 in the atmosphere* and *demand of food and fiber* all with 4 connections. In-degree closeness reports the farthest reachable consequences in the causal pathways. The nodes with highest in-closeness are *loss of predators, loss of herbivores* and *fragmentation* (Figure 6c).

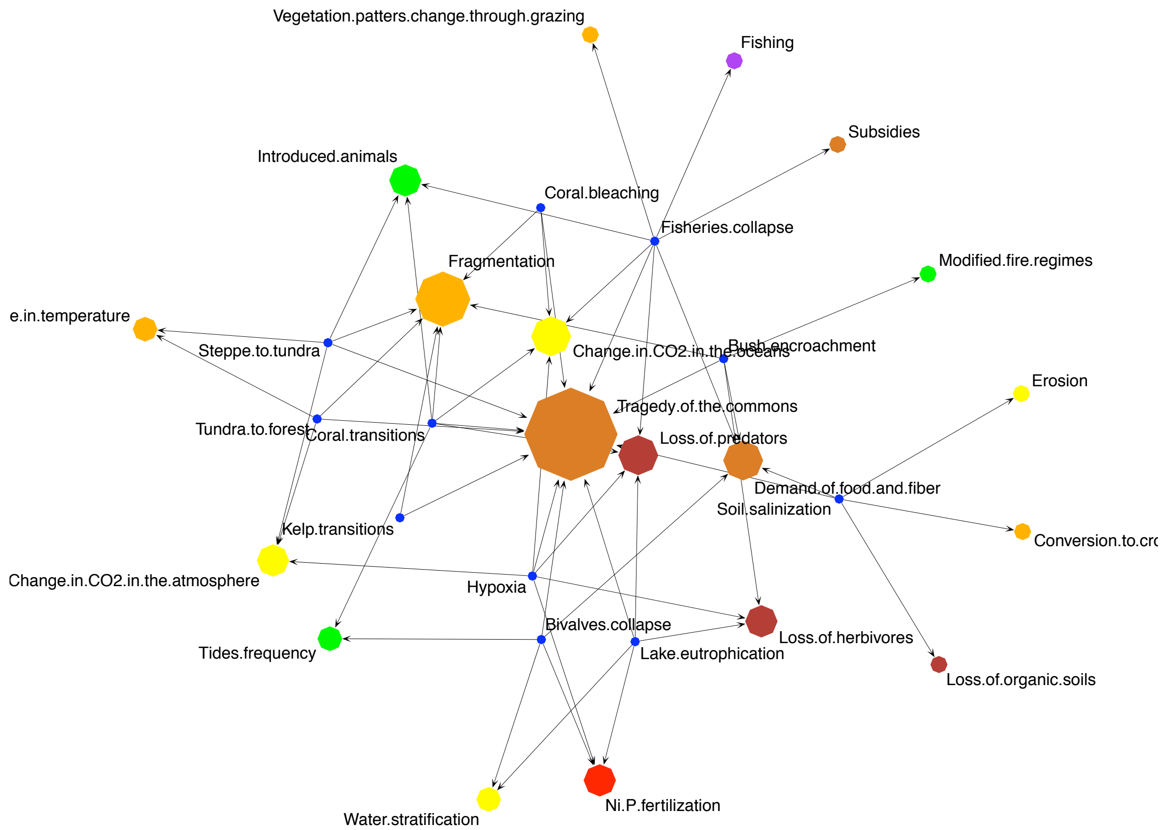


Figure 9. Direct consequences of regime shifts. Node size correspond to in-degree or the number of causation links from regime shifts nodes (in blue). Each color correspond to global change drivers categories in Table 2: Resource exploitation (purple), pollution (red), land use change (orange), climate impacts (yellow), alteration of frequency disturbance (green), alteration of biodiversity (brown), demographics (grey) and economics (chocolate).

Q4. What are the possible cascading effects of regime shifts and its drivers?

We attempted to grasp possible domino effects by looking at causal pathways, especially those between regime shifts. The longest pathway is of 6 degrees of separation, while the average pathway distance is 2.37. We found roughly $6.5 * 10^6$ possible pathways between all nodes. We explored the plausibility of domino effects by looking only at the shortest pathways between regime shifts (n=400). We built an adjacency matrix with the shortest distance between regime shifts nodes. The result was a compact network where all nodes are interconnected, a graph with density 1 - not shown. Given the unexpected high connectivity among regime shifts, all shortest pathways were manually checked and we confirmed their plausibility with the literature review. Accordingly, we classified them in strong pathways when literature supported, weak when there is not explicit mention on the literature but still seems logical, or fake when problematic.

Figure 10 shows the domino effects of regime shifts when looking only shortest pathways. *Soil salinization* is the departing point of most pathways (74), followed by *bush encroachment* (67) and *lake eutrophication* (36). In contrast, when looking only at strong pathways, *soil salinization* (22) is followed by *fisheries collapse* (12) and *tundra to forest* (9). In general, the most problematic connections occur between regime shifts in tropical ecosystems like and regime shifts in temperate ecosystems.

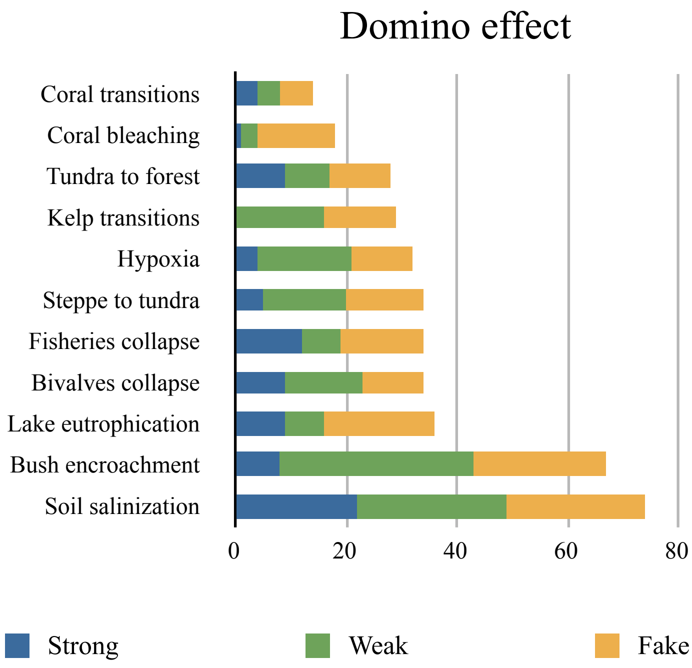


Figure 10. Domino effects. Number of possible shortest pathways between regime shifts nodes. In blue strong pathways, green weak pathways and in yellow fake ones (n=400).

164 pathways were discarded because the causal explanations they embedded were incongruent. However, unconnected regime shifts are expected to be connected when accounting for longer paths. Most strong pathways are associated either with agricultural drivers, such as *conversion to crops, nitrogen and phosphorous fertilization, fragmentation, erosion, loss of organic soil;* or drivers under the demographics and economics categories (Table 2.). Weak pathways consistently concur to climate related drivers, *tragedy of the commons* and *demand for food and fiber.*

DISCUSSION

This study demonstrates the extraordinary potential to combine scientific knowledge from different disciplines and grasp alternative hypotheses about the dynamics underlying regime shifts. In this study we focus on causality, one of the most elusive concepts in science. By using CLD we synthesize alternative explanations about how regime shifts happen in different ecosystems. It also allows creative thinking about possible connections among regime shifts both in time and space. Hence, it opens a window of opportunity to hypothesize about cross-scale interactions. In this section we first discuss the meaning of our results regarding our four guiding questions. Then, we elaborate on the limits of this preliminary analysis and methodological considerations. A reflection about managerial options and further areas of research will be considered before reaching the concluding remarks.

Q1. What are the major global change drivers of regime shifts?

Table 3 briefly summarizes the three most important sets of drivers for each measurement we applied. Although different measures give different results, they are surprisingly consistent for such a small sample. The most frequently measured top driver is *conversion to crops.* Hence, drivers related to agricultural processes regularly show up with e.g. *demand for food and fiber, consumption patterns, nitrogen and phosphorous fertilization,* *external inputs, harvest and resource consumption* and *grazing*. Another key process underlying regime shifts seems to be global warming, however it only appears as an intermediate cause. Therefore, establishing direct causality with particular regime shifts might be a challenge, except for well established cases like coral bleaching.

Table 3. The top three drivers according to different measures. Header colors correspond to the pathway described in Figure 3. Drivers sharing the same level of importance were included.

	RSDB raw data (Figure 4a)	Immediate causes (Figure 5)	Out-degree (Figure 7a)	Betweenness (Figures 6b,7b)	Eigenvector (Figure 7b)	Out-closeness (Figure 7c)
1	Global climate change	Sedimentation	Conversion to crops	Conversion to crops	Conversion to crops	Consumption patterns
2	Harvest and resource consumption	i) Vegetation patterns change through grazing ii) Nitrogen and phosphorous fertilization iii) Fishing	Change in temperature	Tragedy of the commons	Perverse incentives	Technology
3	External inputs	i) Loss of herbivores ii) Loss of predators	Demand for food and fiber	i) Fisheries collapse ii) Change in temperature	i) Subsidies ii) Poverty	Human population growth

Interestingly, demographic and economic drivers seem to have about the same importance as global warming, although they are less studied in the regime shifts literature. This is also the case with *tragedy of the commons, perverse incentives, technology, subsidies, poverty* and *human population growth*. Most of them appear in regime shifts where resource exploitation is strongly related with the main feedback loops, as *fisheries collapse*. However, since they amplify processes like pastoralism and agriculture, they gain importance through the network structure. In addition, all of these drivers act diffusely in the causal pathways (Nelson 2005), making it difficult to establish causality in a rigorous way. This is probably the reason why, despite their importance, they are rare in regime shifts literature.

Note that two observations do not fit very well with the general findings in Table 3. First, *sedimentation* is the most important immediate cause of regime shifts in our sample. Although it can be tracked back to agricultural processes already mentioned, its importance is not necessary due to such a connection. It might also be a consequence of having most of our regime shifts examples in aquatic environments (Figure 4). Second, drivers related to the alteration of biodiversity, though important, only appear as immediate causes.

The last important drivers in the RSDB are *timber production* and *small scale subsistence crop cultivation*. The first is underrepresented since we do not have regime shifts in forests in this preliminary analysis. The second suggests that agriculture needs to be either aggregated in space or intensive in time, to produce regime shifts, given the previous results. Sorted by degree centrality, *heavy metals and persistent organic pollutants* is the least important driver, whereas by betweenness and eigenvector centrality, *change in temperature* and *change in CO_2 in the oceans* are last on the list. Yet again, it might be the result of lacking examples such as trophic cascades (e.g. Moellmann et al. 2008, Alheit 2009, Stouffer and Bascompte 2010), climate-forest interactions (e.g. Oyama and Nobre 2004, Rietkerk et al. 2004, Foley et al. 2005, Dekker et al. 2007, Nobre et al. 2009), or ocean acidification (Hofmann and Schellnhuber 2009). An alternative explanation is that these variables probably are too slow to produce any of the regime shifts documented in the RSDB to date.

Q2. What are the impacts of regime shifts on ecosystems and ecosystem services?

Biodiversity plays a fundamental role as both cause and consequence of abrupt change in ecosystems. Biodiversity is the ecosystem component most affected by regime shifts. On the other hand, biodiversity related variables like *loss of predators* and *loss of herbivores* appear on the top-three list of important drivers (Table 3). Despite its importance, regime shifts associated with biodiversity loss such as *fisheries collapse,* have speculative or contested evidence on their existence and possible causal mechanisms. In fact, biodiversity loss and cascade effects produced by species removal in food webs are still one of the major challenges for theoretical ecologist (Bascompte 2009). Its relation with different regime shifts is an interesting further research field.

Fisheries appears as driver, regime shift (*fisheries collapse*) and the most important provisioning service affected. Fisheries is a hotspot for further research. It is not only one of the most contested examples of regime shifts (Hilborn 2007, Litzow and Urban 2009). Fisheries collapse suffers from the problem of shifting baselines, since our fishing records start at a time when stocks were already severely reduced (Jackson et al. 2001, Ainley and Blight 2009), making identification of fisheries related regime shifts extremely difficult (Jackson 2008, Kirby et al. 2009).

The regulating and supporting services most affected by regime shifts suggest that agricultural development might be affected as well. Not surprisingly *livelihoods and economic activity* and *food and nutrition* are at the top of the impacts to human well being. Consequently, regime shifts might undermine the achievement of at least the first Millennium Development Goal: reduction of hunger and poverty.

Q3. What are the impacts of regime shifts on global change drivers?

Table 4 summarizes our findings when looking at consequences of regime shifts on drivers. Surprisingly, even though we used very different measurements, we obtained similar results. While immediate consequences only showed the most affected drivers by regime shifts with one degree of separation, higher values in in-degree closeness showed furthest drivers reached in the causal pathways on the complete network, including those amplified after a regime shifts has been caused.

It is worth noting that *demand for food and fiber* is closely related to agricultural processes already highlighted. *Tragedy of the commons* is the most exacerbated driver because most of regime shifts, though not all of them, induce resource scarcity on the ecosystem services the desirable state provides, such as fishing, grazing and crop production. When scarcity is high the tragedy of the commons is exacerbated, although it might be overcome by well-designed institutions (Ostrom 1990).

Fragmentation, on the other hand, is an intriguing driver for two reasons. First, independent of its context or ecosystem, it may be related with deterioration of processes related to spatial resilience, such as species migration, meta-population dynamics or dispersion of fire. Fragmentation often involves connecting or disconnecting ecological processes that were not present before. Secondly, landscape patterns might contain information of past events or ecological memory, feeding back the frequency of ecological processes and disturbances including outbreaks or fires (Blarer and Doebeli 1999, Peterson 2002, Stone et al. 2007). For this reason, fragmentation patterns promise to be a fruitful field of research for predicting critical transitions (Peterson 2002, Scheffer et al. 2009).

Table 4. Top three most affected drivers by regime shifts. Drivers sharing the same level of importance were included.

	Immediate consequences (Figure 9)	In- Closeness (Figure 7c)
1	Tragedy of the commons	Loss of predators
2	Fragmentation	Fragmentation
3	i) Loss of predators ii) Change in CO_2 in the atmosphere iii) Demand of food and fiber	Loss of herbivores

Biodiversity appears again, but now as a far reaching consequence of regime shifts. It is not clear why it is important both as near cause and far consequence. It seems to be an underlying process connecting causes and consequences of regime shifts that the RSDB is not able to clearly capture yet.

Q4. What are the possible cascading effects of regime shifts and its drivers?

Cascading effects between regime shifts were explored by looking at shortest pathways. We found an unexpected high connected network. However, if it is so connected, why regime shifts are the exception rather than the rule in reality (Scheffer 2009)? Why they do not happen more often? Likewise the metaphor of the domino effects, such cascade effects need synchrony to occur. If the dominoes are too separated or not well aligned, the effect simply does not happen. If the drivers do not reinforce feedbacks strong enough to push the system to a different basin, regime shifts does not happen (Scheffer 2009). Based on our methods we cannot predict whether drivers are synchronized, but we can certainly explore what pathways might connect different events in time and space. Base on the revision of shortest pathways, we classified them in strong, weak and mistaken.

Mistaken pathways generally points out two kinds of errors. First, spatial mismatch is frequently reported for drivers linking regime shifts in different ecosystems. They are typically under the category alteration of biodiversity in Table 2. For example the *loss of herbivores* caused by bush encroachment is not the same affecting shifts in coral transitions. Second, drivers affecting ecosystem processes work markedly different in terrestrial and marine ecosystems. While *fragmentation* can exacerbate erosive processes in land, in the sea *erosion* appears when tridimensional structures are lost like coral reefs or kelp forest.

Weak pathways are these that show up because they have the shortest distance among two regime shifts but are not well supported by the literature review. Besides, we know that by exploring longer paths we would probably find better explanatory linkages. For instance, *lake eutrophication* reduces fishing productivity, increasing the demand for food; and through the market, sending a signal to increase meat production as an alternative source of protein in other systems. This might increase grazing which in turn is cause of *soil salinization.* Often weak linkages include drivers under demographics or economic categories in Table 2. Another type of weak linkage happens when spatial adjacency is required. Following the example, *soil salinization* causes the loss of organic soil. With less soil both in quality and deepness, the ecosystems tends to develop shorter vegetation, which also means less roots. In consequence, erosion is exacerbated, at that is at the time a driver for lake eutrophication because it brings nutrients and sediments. In this case, the connection among regime shifts occurs iff they are adjacent.

Strong pathways often include already mentioned agriculture related variables, as well as the exacerbation of particular feedbacks on the same ecosystem. *Lake eutrophication*, for instance, involves the release of phosphorous through a recycling feedback, which in turn is one of the causes of *hypoxia*. Some weak paths are related to climate dynamics. However, we think that those would be stronger paths as soon as more climate-related examples are included in the RSDB, such as desertification or forest to savannas. There is a growing body of literature considering ecosystem change as a consequence of climate interactions such as moisture feedbacks (Laurance and Williamson 2001, Oyama and Nobre 2003, Rietkerk et al. 2004, Dekker et al. 2007), change in the frequency of upwellings (Kirby et al. 2009, Bakun et al. 2010) or ENSO events (Behrenfeld et al. 2006, Da Silva et al. 2008). Hypothetically, those feedbacks, for instance, connect deforestation in the Amazon basin with collapse in the Peruvian upwelling system, one of the planet most productive fisheries.

Based on the 400 pathways studied, we intuitively suggest five types of cascading effects among regime shifts. First, the *exacerbation of feedback loops* that links for example lake eutrophication with hypoxia or coral bleaching with coral transitions. Second, the *neighborhood effect* in weak links where adjacency is required. Spatially explicit studies and mapping techniques are promising areas for further research exploring such connections. Third, on *diffuse connections* where the linkage does not depend on spatial adjacency but on the connectivity of the markets, we regroup all the weak links related with market dynamics: global trade of resources, and drivers under demographic and economic categories.

The remaining two types share a scale related pattern. First, regime shifts that have large spatial and slow temporal processes seems to be more influential when comes to *cascading-down* interactions. Second, regime shifts which dynamics are very fast seems to have a role at *cascading-up* other shifts. We believe those scale related patterns are strongly influenced by drivers which change the frequency of the disturbance, such as fire, rain variability, or droughts and floods.

Shortcomings and future research

Although CLD and network analysis are established tools in some research areas (Sterman 2000, Watts 2004), we combined here in an innovative approach to study regime shifts. We gained interesting insights on regime shifts dynamics by combining different sources of scientific knowledge. We also abandoned the single perturbation approach typically used to study regime shifts (Rinaldi and Scheffer 2000, Scheffer 2009) and embrace the multi-causal nature of non-linear changes in ecosystems. By doing so, we acknowledged that regime shifts are tightly connected and the management of immediate causes or well studied variables might not be enough to avoid such catastrophes. Our approach to causality has been qualitative, leaving out of our scope the question if drivers are strong enough to predict regime shifts in concrete cases.

For this reason, a quantitative approach is encouraged. It would be interesting to extract a subgraph from our network and study linkages with differential equations embedded on each edge. How do dynamic thresholds move in the phase space given the interaction of regime shifts drivers is still an unexplored area of research. Another quantitative approach would be assigning probabilities at each edge to explore what is the likelihood of certain causal pathways. The latter combined with a spatially explicit approach can generate maps of areas prone to specific regime shifts not only given the drivers influencing each landscape unit, but also the dynamics underlying change in adjacent systems.

We find two different types of systematic errors. First, we faced a trade-off of generality when defining drivers' categories. Too general drivers often result in mistaken pathways. However, making them more specific might reduce the power of finding unexplored causal pathways. One solution to the problem could be to separately analyze marine and terrestrial ecosystems. Nevertheless, we risk to lose cascading interaction. Another drastic solution would be to directly build the networks on the CLD; but this in turn would make the analysis computationally expensive and it would not guarantee the explanatory power of the resulting pathways.

Our second source of systematic error was the mistaken paths. However, it opens an arena for a new research question: how robust are the causal pathways between regime shifts? It would be interesting to explore the answer by applying graph partitioning methods (Easley and Kleinberg 2010). In other words, by systematically deleting problematic edges among pathways until finding the longest possible path between two regime shifts. We already know that only 6 steps are possible. By doing so, not only all possible paths are calculated, but it could also suggest which ones are more likely to happen in an specific case. Similar approaches has been applied to the study of extinction dynamics in food webs (e.g. Solé and Bascompte 2006).

Other studies have approached to the causes of global change from different perspectives. Lambin *et al.* (2001) explored the causes of land-use and land-cover change, Geist & Lambin (2002, 2004) studied the causes of desertification, and Schellnhuber *et al.* (1999) analyzed syndromes of global change. However, this is the first time networks are used to capture causal relationships regarding ecosystem change. Such studies might be complemented by our approach when looking to the structural connections and sequences of drivers that leads to certain phenomena. One of the benefits of using networks is identifying far reaching causes and consequences that usually are hard to test in reality. For example, Geist & Lambin (2004) found that despite poverty could be a cause of desertification, it does not show a clear correlation across the 132 cases they analyzed. Here we found that demographic and economic drivers are as important as global warming, but they effect is more diffuse given they are an the very beginning of our causal pathways.

Nevertheless, network analysis needs to be further developed to better capture the importance of sequential events, in our case domino effects. Networks methods are typically intended for random graphs. Our representation of regime shifts is far from random, and any statistical modeling should be interpreted cautiously.

Management challenges

This study found that agricultural processes, global warming, biodiversity loss and demographic and economic drivers are the main causes of regime shifts. However, management options at different scales of action are rather scarce.

Biodiversity loss is a process not fully understood (Bascompte 2009). However, some scholars have gained understanding by doing experiments in micro environments that can be applied to higher scales. Bell & Gonzalez (2009) found that evolutionary rescue -the time necessary for a specie to adapt to adversary conditions- from stochastic fluctuations might occur within 25 generations. Gouhier *et al.,* (2010), on the other hand, found that strong environmental fluctuations disrupt species compensatory dynamics, destabilizing metacommunities and reducing species abundance. This suggest that the increasing forcing on global change drivers should slow down enough to allow species adaptation and keep food webs stable.

Gordon *et al*. (2008) identified agriculture as a pivotal regime shift driver. Agriculture when aggregated in space can modify water cycling processes such as moisture feedbacks (Foley et al. 2005) or the balance between green and blue water (Falkenmark and Rockström 2008, Gordon et al. 2008). Scholars also recognize that regime shifts such as hypoxia or eutrophication can only be avoided by managing the input of fertilizers on agricultural land (Carpenter 2003, Diaz and Rosenberg 2008). New methods to close the nutrient cycle on farms are needed in order to avoid drainage of nutrients to water sources (Diaz and Rosenberg 2008).

However, what is caused by agriculture needs to be complemented by what causes agriculture. The role of demographic and economic drivers needs to be further studied. For example, how international trade erode spatial resilience when it comes to food production is still an open question. Weak pathways and diffuse connections represent a challenge for managers, especially when they are socially reinforced or amplified.

Global climate change, biodiversity loss or the demand for food and fiber is hardly manageable in regional to local scales. In addition, they are a policy sensitive matter. They inherently bring into the table the issues of equity, distribution of welfare and human rights. Based on regime shifts literature, we cannot offer major suggestions so far. This fact encourage the study of diffuse or so called indirect drivers of regime shifts. By disentangling the underlying feedback mechanism of indirect drivers, we will probably gain insights on its managerial options.

CONCLUSIONS

The purpose of this paper was to perform an exploratory analysis of the causal interactions among global change drivers of regime shifts. We investigated four major questions: *i)* what are the major global change drivers of regime shifts? *ii)* what are the impacts of regime shifts ecosystem services?, *iii)* what are the impacts of regime shifts on global change drivers, and *iv)* what are the possible cascading effects of regime shifts?

The use of different indicators of importance based on network centrality properties has given us different sets of drivers. Overall, agriculture related processes, global warming, biodiversity loss, and demographic and economic categories group the most important drivers. Fragmentation, biodiversity loss and economic drivers figure as the most frequent consequences. Regimes shifts undermine the achievement of the first Millennium Development Goals: reduction of hunger and poverty, since their most common impacts on human well-being are the reduction of livelihoods and food production.

Global change drivers play a different role when it comes to cause regime shifts. While immediate drivers are often better studied and the responsible for threshold like responses characteristic of regime shifts, middle drivers -or those with high betweenness- are the key players at causing several regime shifts. Hence, they are target for managers. Drivers far from regime shifts in the causal pathway are less studied in the regime shift literature reviewed. However, they can be considered as causal roots. Although establishing direct causality or even correlations in specific cases might be impossible, it does not mean that they should be ignored. Theoretically speaking, smooth changes in such indirect drivers might amplify the effect of more immediate ones, introduce noise or mobilize thresholds towards historically safe points in the system under study.

BIBLIOGRAPHY

Ainley, D. G. and L. K. Blight. 2009. Ecological repercussions of historical fish extraction from the Southern Ocean. Fish Fish **10**:13-38.

Alheit, J. 2009. Consequences of regime shifts for marine food webs. Int J Earth Sci **98**:261-268.

Allesina, S. and M. Pascual. 2009. Googling Food Webs: Can an Eigenvector Measure
Species' Importance for Coextinctions? Plos Computational Biology **5**:e10416. doi:10410.11371/journal.pone.0010416.

Bakun, A., D. Field, A. Redondo-Rodriguez, and S. Weeks. 2010. Greenhouse gas, upwelling-favorable winds, and the future of coastal ocean upwelling ecosystems. Global Change Biol **16**:1213-1228.

Bascompte, J. 2009. Disentangling the Web of Life. Science **325**:416-419.

Behrenfeld, M. J., R. T. O'Malley, D. A. Siegel, C. R. Mcclain, J. L. Sarmiento, G. C. Feldman, A. J. Milligan, P. G. Falkowski, R. M. Letelier, and E. S. Boss. 2006. Climate-driven trends in contemporary ocean productivity. Nature **444**:752-755.

Bell, G. and A. Gonzalez. 2009. Evolutionary rescue can prevent extinction following environmental change. Ecol Lett **12**:942-948.

Bellwood, D., T. Hughes, C. Folke, and M. Nyström. 2004. Confronting the coral reef crisis. Nature **429**:827-833.

Blarer, A. and M. Doebeli. 1999. Resonance effects and outbreaks in ecological time series. Ecol Lett **2**:167-177.

Borgatti, S. P., A. Mehra, D. J. Brass, and G. Labianca. 2009. Network Analysis in the Social Sciences. Science **323**:892-895.

Butts, C., M. Handcock, and D. Hunter. 2008. network: Classes for Relational Data. Irvine, CA. .

Butts, C. T. 2009. sna: Tools for Social Network Analysis.

Carpenter, S., D. Ludwig, and W. Brock. 1999. Management of eutrophication for lakes subject to potentially irreversible change. Ecological Applications **9**:751-771.

Carpenter, S. K., O. 2003. Regime shifts in lake ecosystems: pattern and variation. Ecology Institute.

Csardi, G. and T. Nepusz. 2006. The igraph software package for complex network research. InterJournal, Complex Systems 1695.

Da Silva, R., D. Werth, and R. Avissar. 2008. Regional impacts of future land-cover changes on the amazon basin wet-season climate. J Climate **21**:1153-1170.

Dekker, S. C., M. Rietkerk, and M. F. P. Bierkens. 2007. Coupling microscale vegetation-soil water and macroscale vegetation-precipitation feedbacks in semiarid ecosystems. Global Change Biol **13**:671-678.

Diaz, R. J. and R. Rosenberg. 2008. Spreading Dead Zones and Consequences for Marine Ecosystems. Science **321**:926-929.

Easley, D. and J. Kleinberg. 2010. Networks, Crowds, and Markets: Reasoning About a Highly Connected World. Draft Version February 12, 2010 edition. Cambridge University Press.

Ecosystem Assessment, M. 2005. Ecosystems and human well-being: synthesis.

Falkenmark, M. and J. Rockström. 2008. Building resilience to drought in desertification-prone savannas in Sub-Saharan Africa: The water perspective. Nat. Resour. Forum **32**:93-102.

Foley, J., R. DeFries, G. Asner, C. Barford, G. Bonan, S. Carpenter, F. Chapin, M. Coe, G. Daily, and H. Gibbs. 2005. Global consequences of land use. Science **309**:570-574.

Folke, C., S. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. Gunderson, and C. S. Holling. 2004. REGIME SHIFTS, RESILIENCE, AND BIODIVERSITY IN ECOSYSTEM MANAGEMENT. Annu. Rev. Ecol. Evol. Syst. **35**:557-581.

Geist, H. and E. Lambin. 2002. Proximate causes and underlying driving forces of tropical deforestation. BioScience **52**:143-150.

Geist, H. and E. Lambin. 2004. Dynamic causal patterns of desertification. BioScience **54**:817-829.

Gordon, L. J., G. D. Peterson, and E. M. Bennett. 2008. Agricultural modifications of hydrological flows create ecological surprises. Trends in Ecology & Evolution **23**:211-219.

Gouhier, T. C., F. Guichard, and A. Gonzalez. 2010. Synchrony and Stability of Food Webs in Metacommunities. Am Nat **175**:E16-E34.

Handcock, M. S., D. R. Hunter, C. T. Butts, S. M. Goodreau, and M. Morris. 2003. Software Tools for the Statistical Modeling of Network Data. Project home page at http://statnet.org.

Hilborn, R. 2007. Reinterpreting the State of Fisheries and their Management. Ecosystems **10**:1362-1369.

Hofmann, M. and H.-J. Schellnhuber. 2009. Oceanic acidification affects marine carbon pump and triggers extended marine oxygen holes. P Natl Acad Sci Usa **106**:3017-3022.

Jackson, J. 2008. Ecological extinction and evolution in the brave new ocean. Proceedings of the National Academy of Sciences of the United States of America **105**:11458-11465.

Jackson, J., M. Kirby, W. Berger, K. Bjorndal, L. Botsford, B. Bourque, R. Bradbury, R. Cooke, J. Erlandson, J. Estes, T. Hughes, S. Kidwell, C. Lange, H. Lenihan, J. Pandolfi, C. Peterson, R. Steneck, M. Tegner, and R. Warner. 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science **293**:629-638.

Kirby, R. R., G. Beaugrand, and J. A. Lindley. 2009. Synergistic Effects of Climate and Fishing in a Marine Ecosystem. Ecosystems **12**:548-561.

Lambin, E., B. Turner, H. Geist, S. Agbola, A. Angelsen, J. Bruce, O. Coomes, R. Dirzo, G. Fischer, C. Folke, P. George, K. Homewood, J. Imbernon, R. Leemans, X. Li, E. Moran, M. Mortimore, P. Ramakrishnan, J. Richards, H. Skanes, W. Steffen, G. Stone, U. Svedin, T. Veldkamp, C. Vogel, and J. Xu. 2001. The causes of land-use and land-cover change: moving beyond the myths. Global Environ Chang **11**:261-269.

Laurance, W. and G. Williamson. 2001. Positive feedbacks among forest fragmentation, drought, and climate change in the Amazon. Conservation biology **15**:1529-1535.

Litzow, M. A. and D. Urban. 2009. Fishing through (and up) Alaskan food webs. Can J Fish Aquat Sci **66**:201-211.

Millennium Ecosystem Assessment. 2005. Ecosystems and human well-being: synthesis:137.

Moellmann, C., B. Mueller-Karulis, G. Kornilovs, and M. A. St John. 2008. Effects of climate and overfishing on zooplankton dynamics and ecosystem structure: regime shifts, trophic cascade, and feedback coops in a simple ecosystem. Ices J Mar Sci **65**:302-310.

Nelson, G. 2005. Drivers of ecosystem change: summary chapter. Ecosystems and human well-being: current state and trends: findings of the Condition and Trends Working Group of the Millennium Ecosystem Assessment:73.

Nobre, P., M. Malagutti, D. F. Urbano, R. A. F. De Almeida, and E. Giarolla. 2009. Amazon Deforestation and Climate Change in a Coupled Model Simulation. J Climate **22**:5686.

Ostrom, E. 1990. Governing the commons : the evolution of institutions for collective action.

Oyama, M. and C. Nobre. 2003. A new climate-vegetation equilibrium state for tropical South America. Geophys Res Lett **30**:2199.

Oyama, M. and C. Nobre. 2004. Climatic consequences of a large-scale desertification in northeast Brazil: A GCM simulation study. J Climate **17**:3203-3213.

Peterson, G. 2002. Contagious disturbance, ecological memory, and the emergence of landscape pattern. Ecosystems **5**:329-338.
R Development Core Team. 2009. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
Resilience Alliance & Santa Fe Institute. 2004. Thresholds and alternate states in ecological and social-ecological systems. Resilience Alliance.
Rietkerk, M., S. Dekker, P. de Ruiter, and J. van de Koppel. 2004. Self-organized patchiness and catastrophic shifts in ecosystems. Science **305**:1926-1929.
Rinaldi, S. and M. Scheffer. 2000. Geometric analysis of ecological models with slow and fast processes. Ecosystems **3**:507-521.
Scheffer, M. 2009. Critical transitions in nature and society.
Scheffer, M., J. Bascompte, W. A. Brock, V. Brovkin, S. R. Carpenter, V. Dakos, H. Held, E. H. van Nes, M. Rietkerk, and G. Sugihara. 2009. Early-warning signals for critical transitions. Nature **461**:53-59.
Schellnhuber, H., A. Block, M. Cassel-Gintz, J. Kropp, G. Lammel, W. Lass, R. Lienenkamp, C. Loose, M. Lüdeke, O. Moldenhaver, G. Petschel-Held, M. Plöchl, and F. Reusswig. 1999. Syndromes of Global Change. Gaia **6**:19-34.
Scott, J. 2000. Social Network Analysis A Handbook. Second edition. SAGE Publications, London.
Solé, R. and J. Bascompte. 2006. Self-organization in complex ecosystems.
Steffen, W., P. J. Crutzen, and J. R. McNeill. 2007. The Anthropocene: Are humans now overwhelming the great forces of nature. Ambio **36**:614-621.
Sterman, J. D. 2000. Business dynamics : systems thinking and modeling for a complex world.
Stone, L., R. Olinky, and A. Huppert. 2007. Seasonal dynamics of recurrent epidemics. Nature **446**:533-536.
Stouffer, D. and J. Bascompte. 2010. Understanding food-web persistence from local to global scales. Ecol Lett **13**:154-161.
Ventana Systems. 2010. Vensim: The Ventana Simulation Environment.
Watts, D. J. 2004. The “New” Science of Networks. Annu. Rev. Sociol. **30**:243-270.

Appendices

1. Regime Shifts: conceptual review intended for Wikipedia

What is a Regime Shift?

"A relatively sharp change from one regime to a contrasting one, where a regime is a dynamic "state" of a system with its characteristic stochastic fluctuations and/or cycles" (Scheffer, 2009)

Regime shifts are abrupt changes in a system where a smooth change in a parameter value can trigger a completely different behavior of the system as a whole. Different interpretation and application of this concept can be found in academic literature (Table 1). For example, Carpenter *et al.* (2008) refers to regime shifts as large, long-lasting change in ecosystems. The aim of this section is synthesize the framework where regime shifts can be applied and acknowledge the limitations of the concept.

In ecology the idea of systems with multiple stable states, and therefore prone to regime shifts, can be tracked back to Lewontin (1969). This ideas arose from the application of catastrophic theory (a branch of bifurcation theory in mathematics) to environmental issues. Seminal works such as Non-Meir (1975) grazing systems, May (1977) examples in grazing systems, harvesting systems, insect pests and host-parasitoid systems; Jones and Walters (1976) with fisheries systems; and Ludwig *et al.* (1978) with insects outbreaks are the first notions of regime shifts in ecosystems (Collie *et al.,* 2004; Rinaldi & Scheffer, 2000).

However, bifurcations as a mathematical expression of a system's possible behavior can be found in a wide range of systems from atoms to climate dynamics, including social systems.

There are three qualitative types of change:

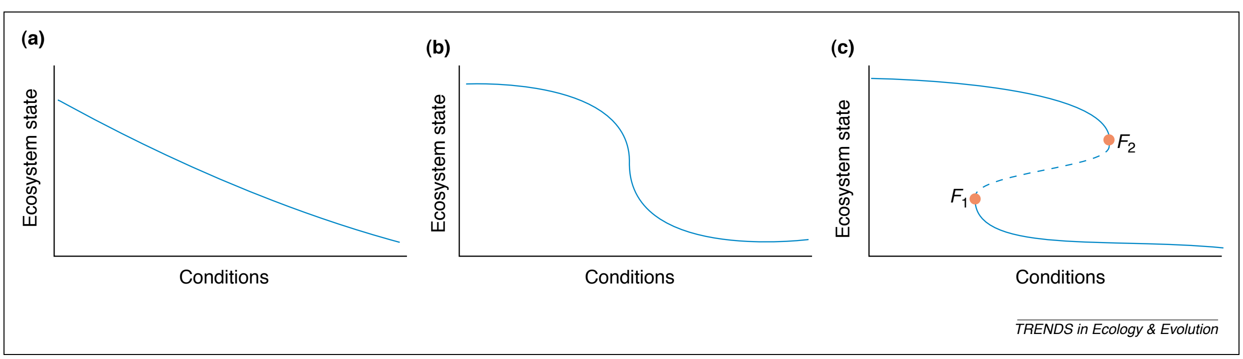


Figure 1. Different ways in which a system can respond to change in conditions (Scheffer & Carpenter, 2003)

Figure 1 represent phase space diagrams -or the change of a variable against other- of a state variable (ecosystem state) respect a set of parameters or conditions. It is important to distinguish between state variables and conditions. The first represents always a fast dynamic in the system and could be termed as fast variable or response variable. The later refers to parameters, forcing variables, control variables or slow variables that often are assumed to be constant but in fact its change rate is slower that the first. Smooth change (a) can be described by a quasi-linear relationship in fast and slow processes. Abrupt change (b) show a non-linear relationship among fast and slow variables meanwhile discontinuous change (c) are characterized by the difference in the trajectory on the fast variable when the slow one increases compared to when it decrease (Collie *et al.*, 2004).

Such difference is termed hysteresis. It means that once the system has flip from the upper to the lower equilibrium (a catastrophic transition), in order to switch the system back it is not enough to restore the conditions present when the system flip. That is the point F2 in the figure 1. Instead, one needs to bring the system further back to point F1. These points are bifurcation points, where the system just jump to another alternative stable state. In this hypothetical case, there is two stable equilibriums and one unstable equilibrium or repeller marked as a dashed line in figure 1c.

In some cases, crossing the threshold brings about a dramatic change in the responding variables while in others the transition in the state variables is more gradual (Folke *et al.*, 2004). Abrupt change has been documented in lake eutrophication (Carpenter 2003) and changes in coral dominance (Bellwood *et al.*, 2004), meanwhile smooth-like change has been documented for encroachment (Walker & Meyers 2004).

That is why a quasi-linear relationship can be assumed to be a regime shift. There could be some sort of slow dynamic that delays the answer of the state variables. In fact, a system that shows smooth change can be prone to be bifurcated by changes in parameters or slow variables (Rinaldi & Scheffer 2000), that is a threshold-like response discussed below. Another possibility is that the state variable chosen is not sensitive enough to the change in the parameters set exposed (Sterman 2002). Moreover, there could be misperception of feedbacks when slow processes and fast processes are thought to be correlated but the causal links are missing or are explained by a third process that is absent in the data or the mental model (Sterman 2002; Dörner 1996).

In addition, the same system might present the whole range of system responses presented in figure 1 because of a structural change in the system. Figure 2 shows the “catastrophe manifold”, where changes in internal structure can bring the system response -the relationship among fast and slow processes- from smooth to discontinuous. Examples of such change in internal structure are trophic interactions, predation patterns or population structures (Collie *et al.*, 2004)

The application of the theory has been controversial in the last decades, at least in ecology. In part because it is difficult to collect enough data, to perform experiments with real systems and to distinguish real bifurcation dynamics from environmental noise (Scheffer & Carpenter, 2003; Scheffer *et al.*, 2009). Given this difficulty, it is not surprising there has been cases where using the same data contradictory conclusions has been found (Overland *et al.*, 2008).

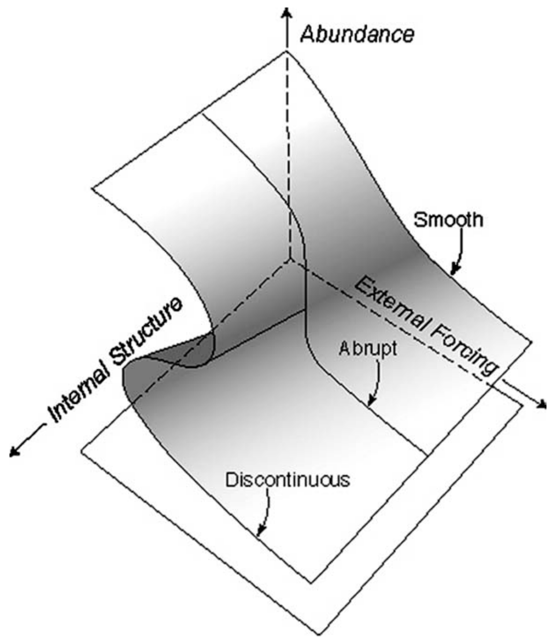


Figure 2. Catastrophe manifold illustrating that the three types of regime shifts are special cases along a continuum of internal ecosystem structure (Collie *et al.*, 2004)

In practice, in order to identify regime shifts, one needs internal dominant self-reinforcing feedback loops (Norberg com. pers.), fast and slow processes at different scales (in time and/or space), and at least the presumption that a non-linear process underlies causal relationships. Bearing in mind such features, here we focus on systems prone to regime shifts, systems that might be in some point in figure 2, rather than systems only exhibit discontinuous change.

In social science, regime shifts has been applied under a slightly different framework. Parallel concepts have been used in social sciences referring to abrupt change in society such as international regimes (Bayles *et al.,* 2008), critical junctions (Pierson 2000; Thelen 1999) or institutional change (Walker and Meyers 2004). Path dependence theory and increasing returns explain phenomena where an attractor is reinforced by feedbacks and the output is generally determined by initial conditions, that is to some extend its history. Scheffer *et al.* (2003) and Brock & Durlauf (1999) present choice models and social interactions while Janssen (2008) present the evolution of cooperation in the prisoner's dilemma.

The evolution of long lasting social arrangement have call the attention of scholars for decades and now it seems to be a good proxy of stability and change in social systems (Walker & Meyers, 2004; Åmark com. pers.). It worth to recall that regime shifts in ecosystems arose from reflexions about the meaning of stability and change in ecosystems (e.g. Lewontin 1969; Holling 1969). Institutions are "laws, informal rules, and conventions that give a durable structure to social interactions, influencing who meets whom, to do what task, with what possible courses of action, and with what consequences of actions jointly taken" (Bowles, 2004:365). Studying regime shifts in social-ecological systems by integrating feedbacks loops between ecosystem process and institutions among scales is still an unexplored research arena.

Table 1. Definitions and applications. Although it does not represent an exhaustive survey, this definitions help to recognize the broad range of application of regime shift concept to different research problems.

Source	Definitions	Modification
Biggs et al 2008	“Ecological regime shifts are large, sudden changes in ecosystems that last of substantial periods of time […] Regime shifts entail changes in the internal dynamics and and feedbacks of an ecosystem that often prevent it from returning to a previous regime, even when the driver that precipitated the shift is reduced or removed […] Regime shifts typically result from a combination of gradual changes in an underlying driving variable (or set of variables), combined with an external shock, such as a storm or fire”	“We defined a regime shift as the period over which the annual increase in the planktivore (*F*) population exceeded 10%. In the model, regime shifts have a typical duration of ≈15 years, reflecting plausible limits on the growth rate of *F*”
Collie et al 2004	“Three different types of regime shift (smooth, abrupt and discontinuous) are identified on the basis of different patterns in the relationship between the response of an ecosystem variable (usually biotic) an some external forcing or condition (control variable). The smooth regime shift is represent by a quasi-linear relationship between the response and control variables. The abrupt regime shift exhibits a nonlinear relationship between the response and control variables, and the discontinuous regime shift is characterized by the trajectory of the response variable differing when the forcing variable increases compared to when it decreases (i.e., the occurrence of alternative “stable” states)”	“”Regime shifts” are considered here to be low-frequency, high-amplitude changes in oceanic conditions that may be especially pronounced in biological variables an propagate through several trophic levels”
Bakun 2004		“persistent radical shift in typical levels of abundance or productivity of multiple important components of marine biological community structure, occurring at multiple trophic levels and on a geographical scale that is at least regional in extent”<
Brock, Carpenter and Scheffer 2008 (Chap 6 in Cumming and Norberg)	“Regime shifts, substantial reorganizations of complex systems with prolonged consequences […] In environmental policy regime shifts raise the prospect that incremental stresses may evoke large, unexpected changes in ecosystem services and human livelihoods”	

Source	Definitions	Modification
Norström *et al.* 2009	"Certain conditions may ultimately result in persistent alternative stable states (ASS), which are characterized by a different set of ecosystems processes, functions and feedback mechanisms..."	"we defined phase shifts as an extensive decreases in coral cover coinciding with substantial increases in some alternative benthic organism, due to a pulse or press disturbance, that have persisted >5yr. A minimum persistence time of 5 yr was used, as this is in accordance with the timeframe of studies describing cases of phase shifts from coral to macroalgal states..."
Andersen *et al.* 2008		"ecological regime shifts can be defined as abrupt changes on several trophic levels leading to rapid ecosystem reconfiguration between alternative states"
Walker & Meyers, 2004	"A regime shift involving alternate stable states occurs when a threshold level of a controlling variable in a system is passed, such that the nature and extend of feedbacks change, resulting in a change of direction (the trajectory) of the system itself. A shift occurs when internal processes of the system (…) have changed and the state of the system […] begins to change in a different direction, toward a different attractor."	
Cumming & Norberg, 2008	"the ability of a system to internally switch between different self reinforcing processes that dominate how the system functions"	

Abrupt change in systems is a field of further development. Application of bifurcation theory has been useful for schizophrenia and parkinson diagnosis for example (Scheffer et al., 2009; Rinaldi & Scheffer 2000). Regime shifts always represent nonlinear relationships between parameters and variables. So, wherever you do find a nonlinear relationship, there is a regime shift to be described.

However, one should bear in mind that emergent process and cross scale interactions are needed in order to be able to identify regime shifts in couple social-ecological systems. In other words, one can find non-linear relationships in both ecological and social systems, but unless those process create feedbacks in the coupled system, it is hard to tell if a non-linear relationship has consequence in the SES scale scope. Some regimes that are present in one subsystem, say the change of political party in a country or the local extinction of a particular specie in an ecosystem, could not represent a regime shift in the SES scale because of the lack of feedbacks. Nevertheless, sometimes it does, and it is those times where we are interested in.

It worth to recall that the idea of abrupt change or regime shifts has been applied in a slightly different way in social sciences. Now lets make it explicit. We human beings have the ability to think in ourselves, and more importantly to do it in time. Hence, we have the ability to visualize the future, to plan and act accordingly. In a collective scale, when whole societies do so, policies are created through deliberation process. However policies are like the dreams of society, they are where we would like to go. Shifts in social systems take steps, first there is a shift in mindsets, then probably there is another in actions and when those actions are aggregated in scale (both in time and space) one can see the collective consequences. It is only when aggregated that those emergent properties acquire meaning in the ecosystem processes scale. However social scientist call regime shifts to e.g. the change of a legal framework in the international arena. Some of them have created feedbacks and have been able to change our relationship with the planet. For example the Montreal protocol to regulate CFC's substances in order to reduce the ozone whole. Others have not reach success at emerging and crossing scales, that is the example of the current climate regime and the negotiations for a protocol in climate change (Bayles *et al.,* 2008).

2. Data capture template

This data capture template is the result of an iterative process in the RSDB group at the Stockholm Resilience Centre. The first version was developed in April 2009. It has changed to better adapt to our examples and has received valuable comments from professors and researchers from the Stockholm Resilience Centre and other departments at Stockholm University.

SES REGIME SHIFT DATABASE

Guidelines for data capture

25 November 2009

GREEN = Free text, paragraph style
BLUE = Free text, brief keywords or phrases
RED = Choose from predefined keyword options

FOR EACH TYPE OF REGIME SHIFT RECORD THE FOLLOWING:

1. **Regime shift name**

Short, succinct name for the type of regime shift (e.g. clear to turbid water shift). The regime shift types should be generalized descriptions of the dynamics of a particular kind of RS as observed over multiple examples, rather than a description of the dynamics of a particular example (e.g. Lake Eutrophication in Lake Mendota). However, for large-scale regional or global RS the case may be unique (e.g. collapse of the thermohaline circulation) and can then be described in unique terms.

2. **Diagram of regime shift dynamics**

A diagram that concisely summarizes the key drivers and dynamics of the regime shift. The figure should consist of 2 or more subfigures depicting the key dynamics and structure of the system in each possible regime. The figure should illustrate the dynamics of the integrated SES, not only the ecological system. Add key labels and text to the figure. Include symbols to indicate the level of reversibility and the links to other regime shifts. See existing figures for further details.

3. **Summary of regime shift**

Brief, clear, easy-to-understand description of how the regime shift works. Clearly identify the alternate regimes and the key drivers (social and ecological). Focus on the most important aspects; more detailed aspects can be included under the next point. This section is intended to be understandable by lay persons and the general public. Limit this section to 1 paragraph, approximately 100 words and do not include references.

4. Description of the alternate regimes and reinforcing feedbacks

A description of the 2 or more alternate regimes, and the reinforcing feedbacks/mechanisms that maintain each regime (if known). Include key references.

5. Drivers that precipitate the regime shift

A description of the key drivers that lead to the regime shift. Where known, explicitly identify the fast and slow variables, as well as important trigger variables. The description should not focus purely on the ecological dynamics, but include anthropogenic links and drivers – i.e. describe the regime shift from an SES perspective. Include key references.

6. Impacts on ecosystems and human well-being

Describe the impacts the regime shift has on i) ecosystems, ii) ecosystem services and iii) human well-being. Include key references.

7. Management options for preventing or reversing regime shift

Describe the options for preventing and reversing the regime shift. Include key references.

8. Links to other regime shifts

List other regime shifts that may be triggered by or that may trigger the current regime shift.

The following fields serve as summaries of the details captured in 3-6, their main purpose being to enable searching and organization of the database.

9. Key direct drivers of the RS

- 9.1. Vegetation conversion and habitat fragmentation
- 9.2. Harvest and resource consumption
- 9.3. External inputs (eg fertilizers, pest control, irrigation)
- 9.4. Adoption of new technology (eg new fishing nets)
- 9.5. Infrastructure development (eg roads, pipelines)
- 9.6. Species introduction or removal
- 9.7. Disease
- 9.8. Soil erosion & land degradation
- 9.9. Environmental shocks (eg fire, floods, droughts)
- 9.10. Global climate change

10. Impacts on ecosystem services

- 10.1. Provisioning services
  - Freshwater
  - Food Crops
  - Livestock
  - Fisheries
  - Wild animal and plant foods
  - Timber

Woodfuel
Other crops (eg cotton)

10.2. Regulating services

Air quality regulation
Climate regulation
Water purification
Water regulation
Regulation of soil erosion
Pest & Disease regulation
Pollination
Natural hazard regulation

10.3. Cultural services

Recreation
Aesthetic values
Knowledge and educational values
Spiritual and religious

10.4. Biodiversity

11. **Impacts on Key Ecosystem Processes**
    11.1. Soil formation
    11.2. Photosynthesis
    11.3. Primary production
    11.4. Nutrient cycling
    11.5. Water cycling

12. **Impacts on Human Well-being**
    12.1. Food and nutrition
    12.2. Health (eg toxins, disease)
    12.3. Livelihoods and economic activity
    12.4. Security of housing & infrastructure
    12.5. Cultural, aesthetic and recreational values
    12.6. Social conflict
    12.7. No direct impact

13. **Ecosystem type in which the RS occurs**
    13.1. Marine & coastal
    13.2. Freshwater lakes & rivers
    13.3. Temperate & Boreal Forests
    13.4. Tropical Forests
    13.5. Moist savannas & woodlands
    13.6. Drylands & deserts (below ~500mm rainfall/year)
    13.7. Grasslands
    13.8. Tundra

13.9. Polar
13.10. Planetary

14. **Land use under which the RS occurs**
    14.1. Urban
    14.2. Small-scale subsistence crop cultivation
    14.3. Large-scale commercial crop cultivation
    14.4. Intensive livestock production (eg feedlots, dairies)
    14.5. Extensive livestock production (natural rangelands)
    14.6. Timber production
    14.7. Fisheries
    14.8. Mining
    14.9. Conservation
    14.10. Tourism
    14.11. Land use impacts are primarily off-site (e.g. dead zones in the ocean caused by fertilizer use in the continental interior; in these cases, also indicate the relevant land uses above)

15. **Typical spatial scale at which RS occurs**
    15.1. Local/landscape (e.g. lake, catchment, community)
    15.2. Sub-continental/regional (e.g. southern Africa, Amazon basin)
    (actual RS mechanism occurs at the regional scale OR cumulative impact/extent of local-scale RS is regional in scale)
    15.3. Global

16. **Typical time scale over which RS occurs**
    16.1. Weeks
    16.2. Months
    16.3. Years
    16.4. Decades
    16.5. Centuries
    16.6. Unknown

17. **Reversibility of RS**
    17.1. Irreversible (on 100 year time scale)
    17.2. Hysteretic
    17.3. Readily reversible
    17.4. Unknown

18. **Confidence: Existence of RS**
    18.1. Speculative – Regime shift has been proposed, but little evidence as yet
    18.2. Contested – Reasonable evidence both for and against the existence of RS
    18.3. Well established – Wide agreement in the literature that the RS exists

19. **Confidence: Mechanism underlying RS**

19.1. Speculative – Mechanism has been proposed, but little evidence as yet

19.2. Contested – Multiple proposed mechanisms, reasonable evidence both for and against different mechanisms

19.3. Well established – Wide agreement on the underlying mechanism

20. **Evidence**

20.1. Models

20.2. Paleo-observation

20.3. Contemporary observations

20.4. Experiments

20.5. Other

21. **Contributors**

Names of those who wrote and reviewed the above info, including their institutional affiliation.

22. **Key References**

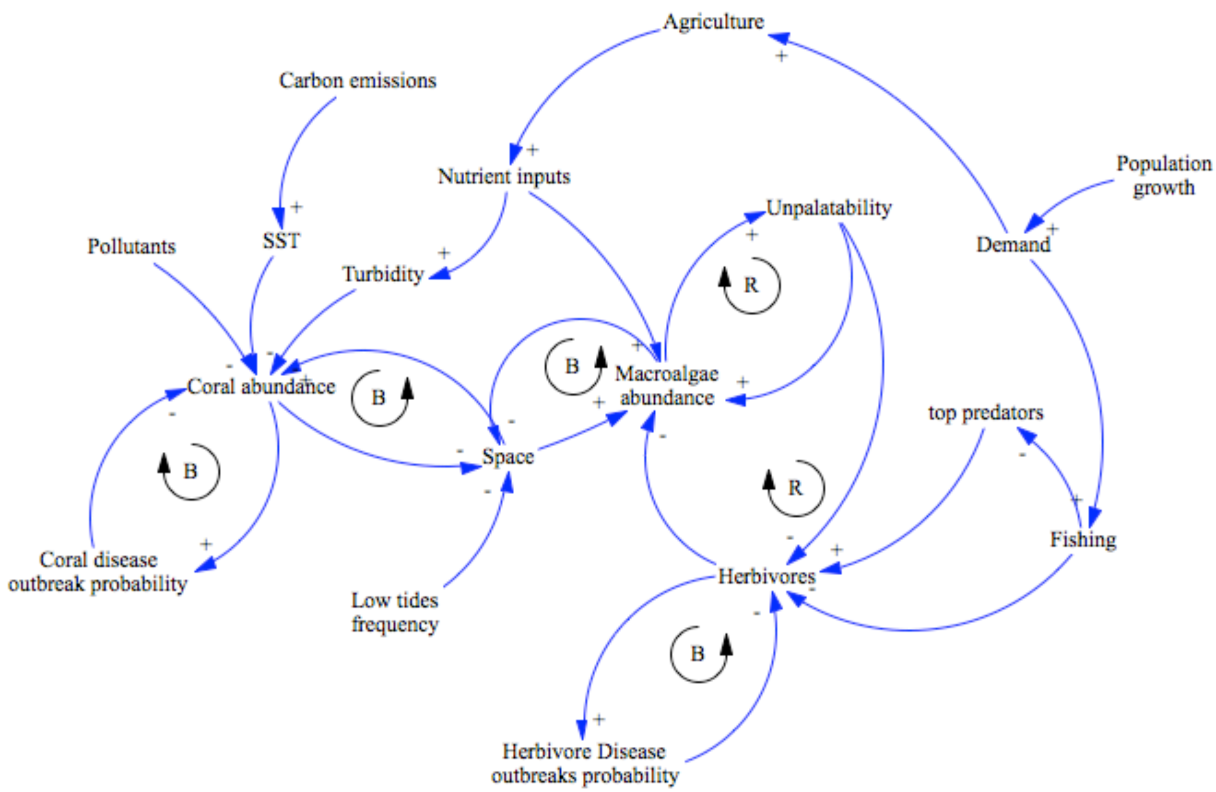
References cited in the paragraph descriptions and other key references

3. Regime shifts examples from the RSDB

CORAL REGIME SHIFTS TRANSITIONS

by Juan Carlos Rocha
juancarlosrochag@gmail.com

2. Diagram



3. Summary

Regime shifts in coral reefs typically involve a change in species dominance from hard corals (3D structure) to seaweed dominance. Less commonly documented shifts include shifts from hard corals to soft coral dominance, corallimorpharians, urchin barrens or sponge dominance. All of these regime shifts result in loss of diversity and structural complexity, and are typically triggered by a combination of overfishing, pollution, diseases and climate change. Loss of biodiversity and coral bleaching make coral systems more vulnerable to such stressors.

4. Description of the regime shift dynamics

Regime shifts in coral systems are usually associated with a change in the species dominance of this ecological community, and consequent changes in the ecosystem structure. Coral reefs are marine ecosystems, three-dimensional shallow-water structures dominated by sclearactinean or hard corals (Bellwood *et al.* 2004). The most well documented regime shifts entail shifts from hard coral to fleshy seaweed (macroalgae) dominance. However, shifts from hard coral to corallimorpharians dominance, soft coral dominance, sponge dominance, and urchin barrens states have also been documented (Norström *et al.* 2009).

Regime shifts are usually driven by multiple drivers, including overfishing, pollution, disease (coral bleaching e.g. Mumby *et al.* 2007) and climate change (Bellwood *et al.* 2004). Reduced herbivory, especially by herbivorous fish, leads to increasing macroalgal abundance due to reduced grazing (Mumby *et al.* 2007). At the same time, pulse disturbances such as low-tides, high sea surface temperatures, and oil pills, lead to events of mass coral mortality (Bellwood *et al.* 2004; Walker & Salt 2004). The combined effect of seaweed growing pressure plus pulse disturbances typically triggers the regime shift.

When coral cover is reduced there is increased colonization by algae, which in turn inhibits coral recruitment – i.e., a positive feedback exists (Norström *et al.* 2009; Mumby *et al.* 2007). Herbivores (mainly fish) control the growth of algae through grazing, scraping, and bioeroding (Nyström 2006). However, once algae reach a certain size they become unpalatable (Scheffer *et al.* 2008). When the abundance of fish is reduced, the ability to react to algal growth peaks is reduced as well, and bed of algae may establish. Hence, diseases in key herbivore species (Nyström *et al.* 2008) can initiate a positive feedback that can lock the system into an alternative regime dominated by macroalgae.

In terms of the regime shift dynamics, the fast variables are the relative abundance of coral and algae, whereas the slow variables are the densities of herbivores. Coral bleaching and loss of biodiversity in functional groups are processes that increase the vulnerability to regime shifts (Bellwood *et al.* 2004).

5. Impact on ecosystems, ecosystem services and human well-being

When coral reefs shift from hard coral to algae-dominant ecosystems, losses in ecosystem services associated with tourism, fisheries, coastal land and ecosystem protection, provision of primary production, as well as biodiversity conservation occur.

Regime shifts to macro-algae dominance have severe impacts on biodiversity and ecological complexity. Up to 60 000 species of plants and animals live in coral reef ecosystems (Moberg & Folke 1999). Despite coral reefs only occupying between 0.1 and 0.5% of the ocean floor, they produce up to 10% of fish consumed by humans (Moberg & Folke 1999). When coral reef ecosystems shift from coral dominance to macro-algae dominance there is typically a substantial decline in the diversity of organisms living on the reef. Such regime shifts are therefore often also associated with the collapse of valuable fisheries.

Regime shifts in the coral community result in a reduction in ecosystem services such as calcium fixation, water cleansing, support of pelagic food webs, as well as fisheries (Moberg & Folke 1999). Constanza et al. (1997) estimated the value of coral reefs services at up to US$ 6 075 per hectare per year based on their contribution to disturbance regulation, waste treatment, biological control, refuge habitat, food production, raw materials, recreation and cultural values. Many of these services are lost or substantially reduced when regime shifts from coral to algae dominance occur. The collapse of coral fisheries also results in unemployment for fishermen, impacts on local economies and reduction of food production. Recreational services (primarily based around diving and snorkelling) are diminished when regime shifts occur, causing losses estimated at up to AUS$ 682 million in the Great Barrier Reef and US$ 8.9 billion for the Caribbean, in addition to 350 000 jobs related in the Caribbean (Moberg & Folke 1999)

Regime shifts in coral reefs can also lead to increased coastal erosion by currents and waves as the buffering service provided by hard coral structures is lost. Increased erosion can have costly impacts on coastal infrastructure and the formation of sand beaches. In addition, increased erosion can lead to the degradation or loss of other coastal ecosystems such as mangroves and sea-grasses areas, which provide valuable ecosystem services such as fish nurseries (Moberg & Folke 1999).

6. Management options for preventing and reversing the regime shift

Due to the multi-causal nature of coral regime shifts, scholars emphasise the necessity of managing coral reefs using an ecosystem approach. Such an approach means taking into account the interaction between land and sea, as well as the scale and origin of the stressors when making decisions at different scales of governance (Moberg & Folke 1999). It is also important to manage the spatial resilience of coral reefs. That is, to manage connectivity, metapopulation dynamics, and to take into consideration the spatial distribution of coral reefs (Moberg & Folke 1999; Nyström et al. 2008). This is because large-scale regional shifts are typically preceded by smaller-scale localized shifts. Therefore, monitoring the occurrence and spatial distribution of smaller-scale regime shifts may help to anticipate, and potentially avert, large-scale catastrophic shifts (Nöstrom et al. 2009).

Herbivores are a key driver that can be actively managed since reduced grazing increases the vulnerability to regime shifts (Mumby et al. 2007). For example, herbivorous fish like parrotfish can be protected. It has been suggested that markets should be transformed to incorporate a body of incentives to prevent the depletion of species in critical functional groups (Bellwood et al. 2004). The abundance of sea urchins should also be carefully managed because urchin dominance can produce negative effects on coral recruitment (Nöstrom et al. 2009).

Bellwood et al. (2004) recommend increasing the rate of establishment and size of no-take areas, including 'cool-spots' of biodiversity. The reason is that areas with low species richness may be more vulnerable, as they may have lost functional groups, or may have low functional redundancy. Hence, minor changes in such ecosystems might trigger regime shifts locally, and erode spatial resilience regionally.

7. Related regimes

Coral bleaching, oceanic eutrophication, fisheries collapse

Key direct drivers of the RS

- 7.1. Habitat conversion or fragmentation
- 7.2. Harvest and resource consumption
- 7.3. External inputs (eg fertilizers, pest control, irrigation)
- 7.4. Adoption of new technology (eg new fishing nets)
- 7.5. Infrastructure development (eg roads, pipelines)
- 7.6. Species introduction or removal
- 7.7. Disease
- 7.8. Soil erosion & land degradation
- 7.9. Environmental shocks (eg fire, floods, droughts)
- 7.10. Global climate change

Impacts on ecosystem services

- 7.11. Provisioning services:
  - 7.11.1. Freshwater
  - 7.11.2. Food Crops
  - 7.11.3. Livestock
  - 7.11.4. Fisheries
  - 7.11.5. Wild animal and plant foods
  - 7.11.6. Timber
  - 7.11.7. Woodfuel
  - 7.11.8. Other crops (eg cotton)
- 7.12. Regulating services
  - 7.12.1. Air quality regulation
  - 7.12.2. Climate regulation
  - 7.12.3. Water purification
  - 7.12.4. Water regulation
  - 7.12.5. Regulation of soil erosion
  - 7.12.6. Pest & Disease regulation
  - 7.12.7. Pollination
  - 7.12.8. Natural hazard regulation
- 7.13. Cultural services
  - 7.13.1. Recreation
  - 7.13.2. Aesthetic values
  - 7.13.3. Knowledge and educational values
  - 7.13.4. Spiritual and religious
- 7.14. Biodiversity

Impacts on Key Ecosystem Processes

- 7.15. Soil formation
- 7.16. Photosynthesis
- 7.17. Primary production
- 7.18. Nutrient cycling

7.19. Water cycling

Impacts on Human Well-being

7.20. Food and nutrition
7.21. Health (eg toxins, disease)
7.22. Livelihoods and economic activity
7.23. Security of housing & infrastructure
7.24. Cultural, aesthetic and recreational values
7.25. Social conflict
7.26. No direct impact

Ecosystem type in which the RS occurs

7.27. Marine & coastal
7.28. Freshwater lakes & rivers
7.29. Temperate & Boreal Forests
7.30. Tropical Forests
7.31. Moist savannas & woodlands
7.32. Drylands & deserts (below ~500mm rainfall/year)
7.33. Grasslands
7.34. Tundra
7.35. Polar
7.36. Planetary

Land use under which the RS occurs

7.37. Urban
7.38. Small-scale subsistence crop cultivation
7.39. Large-scale commercial crop cultivation
7.40. Intensive livestock production (eg feedlots, dairies)
7.41. Extensive livestock production (natural rangelands)
7.42. Timber production
7.43. Fisheries
7.44. Mining
7.45. Conservation
7.46. Tourism
7.47. Land use impacts are primarily off-site (e.g. dead zones in the ocean caused by fertilizer use in the continental interior; in these cases, also indicate the relevant land uses above)

Typical spatial scale at which RS occurs

7.48. Local/landscape (e.g. lake, catchment, community)

Sub-continental/regional (e.g. southern Africa, Amazon basin) (actual RS mechanism occurs at the regional scale OR cumulative impact/extent of local-scale RS is regional in scale)

7.49. Global

Typical time scale over which RS occurs

7.50. Weeks
7.51. Months
7.52. Years
7.53. Decades
7.54. Centuries
7.55. Unknown

Reversibility of RS

7.56. Irreversible
7.57. Hysteretic
7.58. Readily reversible
7.59. Unknown

Confidence: Existence of RS (IPCC language)

7.60. Speculative – Regime shift has been proposed, but little evidence as yet
7.61. Contested – Reasonable evidence both for and against the existence of RS
7.62. Well established – Wide agreement in the literature that the RS exists

Confidence: Mechanism underlying RS (IPCC language)

7.63. Speculative – Regime shift has been proposed, but little evidence as yet
7.64. Contested – Reasonable evidence both for and against the existence of RS
7.65. Well established – Wide agreement in the literature that the RS exists

Evidence

7.66. Models
7.67. Paleo-observation
7.68. Contemporary observations
7.69. Other

Contributor and Reviewer
Juan Carlos Rocha
Intern at Stockholm Resilience Centre and Beijer Institute
juancarlosrochag@gmail.com

Last updated: September 3, 2009

Key References

Bellwood, D.R., Hughes, T.P., Folke, C., and Nyström, M. 2004. Confronting the coral reef crisis. Nature 429:827-33

Costanza, Robert; d'Arge, Ralph; de Groot, Rudolf; Farber, Stephen; Grasso, Monica; Hannon, Bruce; Limburg, Karin; Naeem, Shahid; O'Neill, Robert V.; Paruelo, Jose; Raskin, Robert G.; Sutton, Paul; and van den Belt, Marjan. 1997. The value of the world's ecosystem services and natural capital. Nature 387 (**6630**): 253-260

Moberg, Fredrik and Carl Folke. 1999. Ecological goods and services of coral reefs ecosystems. Ecological Economics 29: 215-33

Mumby, Peter; Hastings, Alan; and Edwards Helen J. 2007. Thresholds and the resilience of Caribbean coral reefs. Nature 450: 98-101

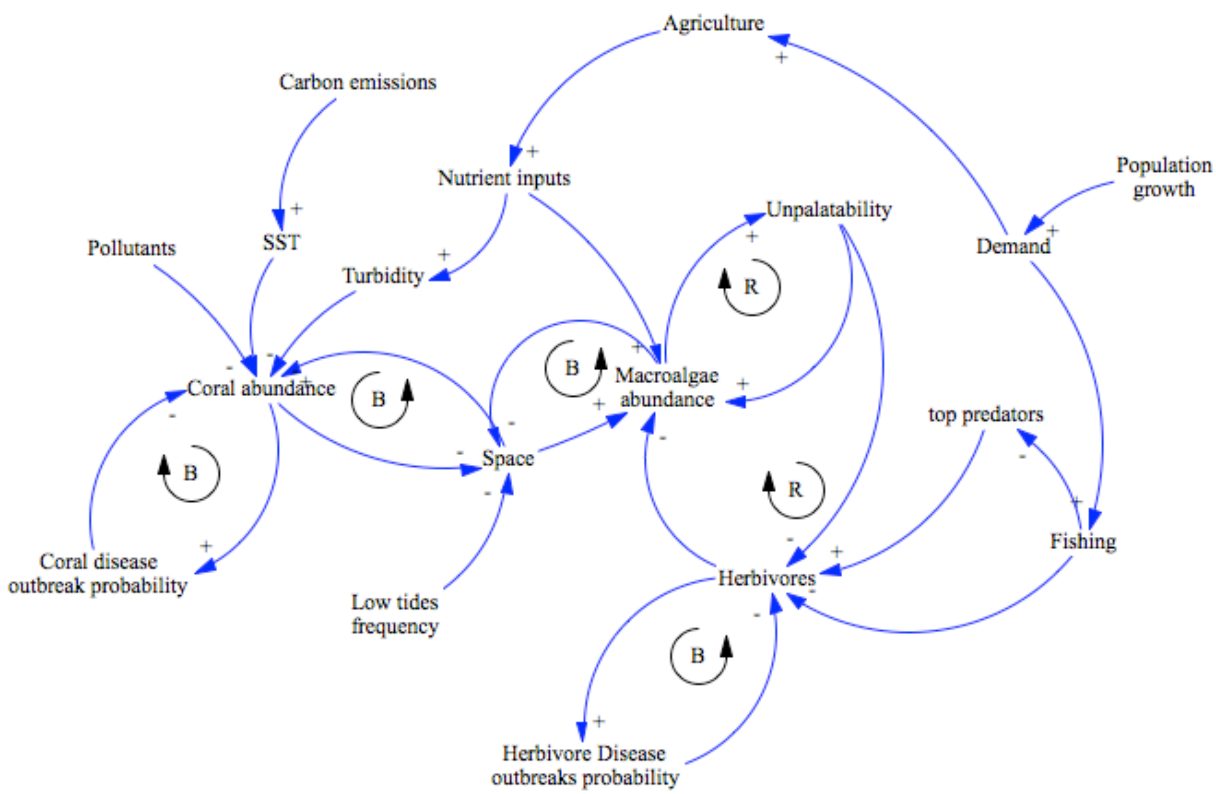
Norström, Albert V; Nyström, Magnus; Lokrantz, Jerker; and Folke Carl. 2009. Alternative states on coral reefs: beyond coral-macroalgal phase shifts. Marine Ecology Progress Series 376:295-306

Scheffer, Marten; van Nes, Egbert; Holmgren, Milena, and Terry Hughes. 2008. Pulse-Driven Loss of Top-Down control: The Critical-Rate Hypothesis. Ecosystems 11:226-237

Walker, B & D. Salt. 2004. Resilience thinking: sustaining ecosystems and people ina changing world. Island Press. Washington. 174p

CORAL REGIME SHIFTS: coral bleaching
by Juan Carlos Rocha
juancarlosrochag@gmail.com

2. Diagram



3. Summary

Coral bleaching is the loss of colour from corals and occurs when symbiotic algae (zooxanthellae) are released from the coral polyps due to stress, usually driven by high sea surface temperature. This bleaching process can trigger mass coral mortality and has been recorded more frequently in recent decades. Mass-bleaching events are expected to increase due to climate change. Mass coral mortality changes the community structure of coral reefs, which is in itself a driver of related regime shifts like fisheries collapse and shifts to algae-dominance.

4. Description of the regime shift dynamics

Coral bleaching is a trigger for other regime shifts in coral reefs (e.g. hard coral to marco-algae shifts), but it can also be seen as a regime shift in itself. The mechanism underlying the shift takes place in the polyps, tiny animals which form the colonies we know as corals. Microscopic algae called zooxanthellae live inside the polyps. Corals and zooxanthellae are symbiotic organisms. Corals receive food from the algae, which have the ability to photosynthesize. The algae also facilitate skeletal growth and provide corals with their colour. In return, corals offer the algae nutrients (nitrogen, phosphorous and carbon dioxide) and protection from predators. Under certain stress conditions, corals release the algae, leading to the loss of coral colour. Hence the term coral bleaching.

Several causes of coral bleaching have been discussed, such as diseases, oxygen toxicity, high ultraviolet light exposure, salinity and pollution (eutrophication). However, it is widely recognized that high sea surface temperature and high light levels are the most correlated drivers (Berkelmans *et al*. 2004; Goreau *et al*. 1994). If temperatures exceed summer maxima by 1º to 2ºC for over 3 weeks, then bleaching will occur, with more sever bleaching as thermal anomalies intensify and lengthen (Hoegh-Guldberg *et. al* 2007). Berkelmans *et al.* (2004) found that in the Great Barrier Reef, Australia, the maximum sea surface temperature (SST) over any 3 day period during the bleaching season (summer) predicted the presence/absence of bleaching with 73.2% accuracy. They also describe that bleaching is more likely to happen to inshore rather than offshore reefs. The occurrence of bleaching depends on the tolerance of the polyp and the zooxanthellae to the warm water.

Massive events of coral bleaching have been recorded more often recently (Berkelmans *et al*. 2004). According to model predictions, coral bleaching events are expected to become increasingly frequent and severe in the coming decades due to global warming (Wooldridge *et al*. 2005). Corals may survive and recover from bleaching after mild thermal stress, but typically show reduced growth, calcification, and fecundity and may experience greater incidences of coral disease (Hoegh-Guldberg 1999, Bruno et al. 2007). Recovery will also be dependent on there being low pressure from algae growth and if there is sufficient polyp recruitment in the next cohort (Goreau *et al.* 1994). Hence, metapopulation dynamics become an important source of recovery. The spatial distribution of the bleaching affects spatial resilience to additional bleaching events and other coral regime shifts.

5. Impact on ecosystems, ecosystem services and human well-being

Coral bleaching can lead to mass coral mortality, radically changing the composition of the ecological community. The ecosystem becomes prone to algae dominance with implications for the trophic food web and biodiversity. This in turn reduces the value of the ecosystem to humans. In the short term, fisheries and tourism are directly affected. In the long term (decades to centuries), coral bleaching and mortality has implications for shore protection, calcium fixation and the ability to adapt to rising sea level (Done 1992; Goreau *et al.*1994).

Up to 60 000 species of plants and animals are hosted in coral reef ecosystems (Moberg & Folke 1999). In over 100 countries, coral reefs are major natural and economic resource (Goreau *et al.* 1994). Despite occupying only between 0.1 and 0.5% of the ocean floor, coral reefs produce up to 10% of fish consumed by humans (Moberg & Folke 1999). Regime shifts in coral reefs are often associated with collapsing fisheries, which reduce food production, lead to unemployment for fishermen, and impact local economies.

Coral mortality can also lead to increased coastal erosion by currents and waves as the buffering service provided by hard coral structures is lost. Increased erosion can have costly impacts on coastal infrastructure and the formation of sand beaches. In addition, increased erosion can lead to the degradation or loss of other coastal ecosystems such as mangroves and sea-grass areas, which provide valuable ecosystem services such as fish nurseries. Among other services, calcium fixation, water cleansing, support of pelagic food webs, as well as fisheries are expected to be significantly reduced through degradation of coastal ecosystems (Moberg & Folke 1999).

Constanza *et al.* (1997) estimated the value of coral reefs services at up to US$ 6 075 per hectare per year based on their contribution to disturbance regulation, waste treatment, biological control, refuge habitat, food production, raw materials, recreation and cultural values. In addition to the collapse of fisheries and resultant impacts on food production and local economies, recreational services (primarily based around diving and snorkelling) are diminished when regime shifts occur, causing losses estimated at up to AUS$ 682 million in the Great Barrier Reef and US$ 8.9 billion for the Caribbean, in addition to 350 000 jobs related in the Caribbean (Moberg & Folke 1999). Coral reefs support cultural and spiritual values such as religious rituals, cultural traditions and institutional frameworks for cooperative fishing, especially in small scale fishing communities (Moberg & Folke 1999).

6. Management options for preventing and reversing the regime shift

"*The persistence of hard coral dominated reefscapes beyond 2050 will be heavily reliant on 2 things, the ability of corals to increase their upper thermal bleaching limits by ~0.1°C per decade, and management that produce local conditions that constrain excessive algal biomass proliferation during inter-disturbance intervals*" (Wooldridge *et al.* 2005).

It is uncertain how fast and whether coral reefs can adapt to the changing climate and expected sea surface temperature increases. But management options do exist. Herbivory management is the most widely used strategy since changes in algal grazing pressure directly affect the vulnerability of coral reefs to regime shifts (Mumby *et al*. 2007). For example, herbivorous fish like parrotfish can be protected. The abundance of sea urchin should be carefully managed because urchin dominance can negatively affect coral recruitment (Nörstrom *et al.* 2009).

Management of the spatial resilience of coral reefs is also important – that is, management of connectivity, metapopulation dynamics, and consideration of the spatial distribution of coral reefs (Moberg & Folke 1999; Nyström *et al.* 2008). In addition, the spatial patchiness or clustering of bleaching events should be considered (Berkelmans *et al.* 2004). Monitoring the occurrence and spatial distribution of local-scale regime shifts may help anticipate, and potentially avert, catastrophic large-scale regional shifts in coral reef ecosystems (Nörstrom *et al*. 2009).

At the regional and local levels, improvements in water quality (through management of land-based sources of pollution), no-take zones and reduction of fishing pressure can contribute to the restoration of ecosystem function and biodiversity (Wooldridge *et al.* 2005). These conditions increase the probability of survival of those corals that develop mechanisms of acclimatization.

7. Related regime shifts

Hard coral to algae dominance
Oceanic eutrophication
Fisheries collapse

Key direct drivers of the RS

- 7.1.Habitat conversion or fragmentation
- 7.2.Harvest and resource consumption
- 7.3.External inputs (eg fertilizers, pest control, irrigation)
- 7.4.Adoption of new technology (eg new fishing nets)
- 7.5.Infrastructure development (eg roads, pipelines)
- 7.6.Species introduction or removal
- 7.7.Disease
- 7.8.Soil erosion & land degradation
- 7.9.Environmental shocks (eg fire, floods, droughts)
- 7.10.Global climate change

Impacts on ecosystem services

- 7.11.Provisioning services:
  - 7.11.1. Freshwater
  - 7.11.2. Food Crops
  - 7.11.3. Livestock
  - 7.11.4. Fisheries
  - 7.11.5. Wild animal and plant foods
  - 7.11.6. Timber
  - 7.11.7. Woodfuel
  - 7.11.8. Other crops (eg cotton)
- 7.12.Regulating services
  - 7.12.1. Air quality regulation
  - 7.12.2. Climate regulation
  - 7.12.3. Water purification
  - 7.12.4. Water regulation
  - 7.12.5. Regulation of soil erosion
  - 7.12.6. Pest & Disease regulation
  - 7.12.7. Pollination
  - 7.12.8. Natural hazard regulation
- 7.13.Cultural services
  - 7.13.1. Recreation
  - 7.13.2. Aesthetic values
  - 7.13.3. Knowledge and educational values

7.13.4. Spiritual and religious
7.14. Biodiversity

Impacts on Key Ecosystem Processes
7.15. Soil formation
7.16. Photosynthesis and primary production
7.17. Nutrient cycling
7.18. Water cycling

Impacts on Human Well-being
7.19. Food and nutrition
7.20. Health (eg toxins, disease)
7.21. Livelihoods and economic activity
7.22. Security of housing & infrastructure
7.23. Cultural, aesthetic and recreational values
7.24. Social conflict
7.25. No direct impact

Ecosystem type in which the RS occurs
7.26. Marine & coastal
7.27. Freshwater lakes & rivers
7.28. Temperate & Boreal Forests
7.29. Tropical Forests
7.30. Moist savannas & woodlands
7.31. Drylands & deserts (below ~500mm rainfall/year)
7.32. Grasslands
7.33. Tundra
7.34. Polar
7.35. Planetary

Land use under which the RS occurs
7.36. Urban
7.37. Small-scale subsistence crop cultivation
7.38. Large-scale commercial crop cultivation
7.39. Intensive livestock production (eg feedlots, dairies)
7.40. Extensive livestock production (natural rangelands)
7.41. Timber production
7.42. Fisheries
7.43. Mining
7.44. Conservation
7.45. Tourism
7.46. Land use impacts are primarily off-site (e.g. dead zones in the ocean caused by fertilizer use in the continental interior; in these cases, also indicate the relevant land uses above)

Typical spatial scale at which RS occurs

7.47. Local/landscape (e.g. lake, catchment, community)
7.48. Sub-continental/regional (e.g. southern Africa, Amazon basin)
(actual RS mechanism occurs at the regional scale OR cumulative impact/extent of local-scale RS is regional in scale)
7.49. Global

Typical time scale over which RS occurs

7.50. Weeks
7.51. Months
7.52. Years
7.53. Decades
7.54. Centuries
7.55. Unknown

Reversibility of RS

7.56. Irreversible
7.57. Hysteretic
7.58. Readily reversible
7.59. Unknown

Confidence: Existence of RS (IPCC language)

7.60. Speculative – Regime shift has been proposed, but little evidence as yet
7.61. Contested – Reasonable evidence both for and against the existence of RS
7.62. Well established – Wide agreement in the literature that the RS exists

Confidence: Mechanism underlying RS (IPCC language)

7.63. Speculative – Regime shift has been proposed, but little evidence as yet
7.64. Contested – Reasonable evidence both for and against the existence of RS
7.65. Well established – Wide agreement in the literature that the RS exists

Evidence

7.66. Models
7.67. Paleo-observation
7.68. Contemporary observations
7.69. Experiments
7.70. Other

Contributor and Reviewer
Juan Carlos Rocha
Intern at Stockholm Resilience Centre and Beijer Institute
juancarlosrochag@gmail.com

Albert Nörstrom, Depatment of Systems Ecology, SU

Last updated: September 3, 2009

Key References

Berkelmans, Ray; De'ath, Glenn; Kininmonth, Stuart; and Skirving, William J. 2004. A comparison of the 1998 and 2002 coral bleaching events on the Great Barrier Reef: spatial correlation, patterns, and predictions. Coral Reefs 23:74-83

Bruno JF, Selig ER, Casey KS, Page CA, Willis BL, Harvell CD, Sweatman H, Melendy AM (2007) Thermal stress and coral cover as drivers of coral disease outbreaks. Plos Biology 5:1220-1227

Costanza, Robert; d'Arge, Ralph; de Groot, Rudolf; Farber, Stephen; Grasso, Monica; Hannon, Bruce; Limburg, Karin; Naeem, Shahid; O'Neill, Robert V.; Paruelo, Jose; Raskin, Robert G.; Sutton, Paul; and van den Belt, Marjan. 1997. The value of the world's ecosystem services and natural capital. Nature 387 (6630): 253-260

Done, Terry J. 1992. Phase shifts in coral reef community and their ecological significance. Hydrobiologia 247: 121-32

Goreau, Thomas J; and Raymond L. Hayes. 1994. Coral Bleaching and Ocean "Hot Spots". Ambio 23 (3):176-80

Hoegh-Guldberg O (1999) Climate change, coral bleaching and the future of the world's coral reefs. Mar Freshwater Res 50:839-866

Hoegh-Guldberg O, Mumby PJ, Hooten AJ, Steneck RS, Greenfield P, Gomez E, Harvell CD, Sale PF, Edwards AJ, Caldeira K, Knowlton N, Eakin CM, Iglesias-Prieto R, Muthiga N, Bradbury RH, Dubi A, Hatziolos ME (2007) Coral reefs under rapid climate change and ocean acidification. Science 318:1737-1742

Moberg, Fredrik and Carl Folke. 1999. Ecological goods and services of coral reefs ecosystems. Ecological Economics 29: 215-33

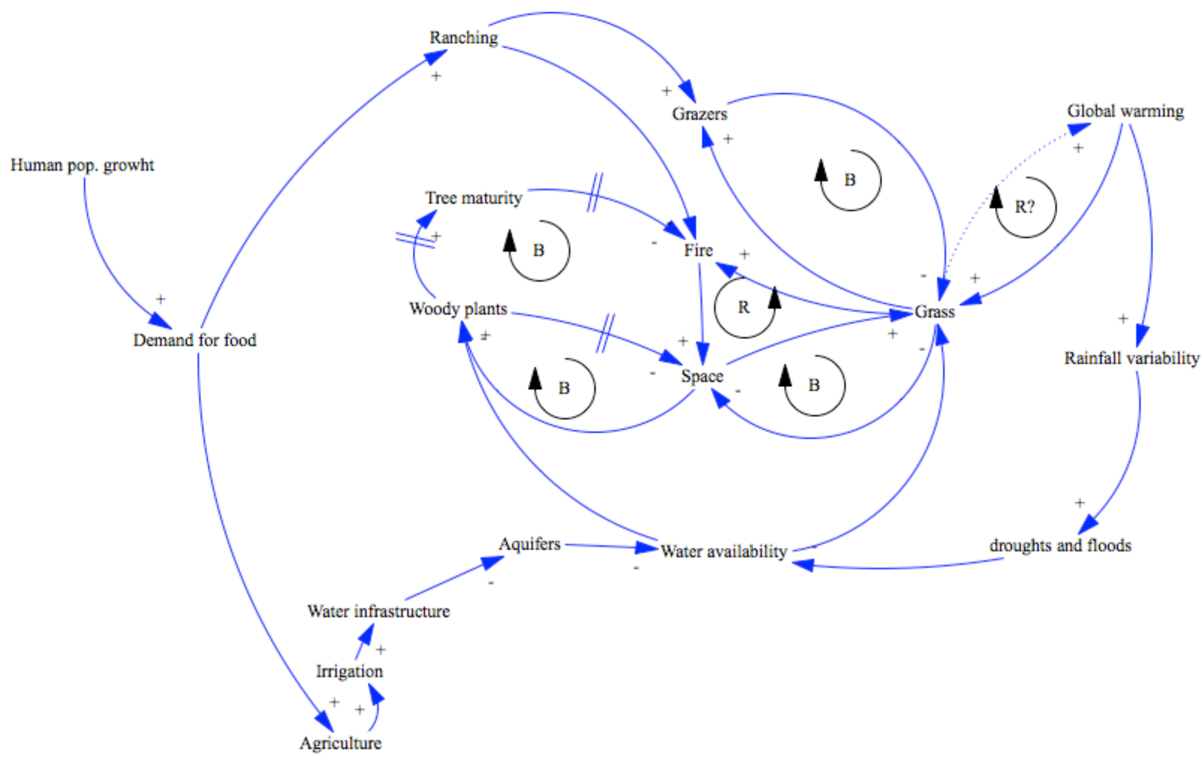
Mumby, Peter; Hastings, Alan; and Edwards Helen J. 2007. Thresholds and the resilience of Caribbean coral reefs. Nature 450: 98-101

Norström, Albert V; Nyström, Magnus; Lokrantz, Jerker; and Folke Carl. 2009. Alternative states on coral reefs: beyond coral-macroalgal phase shifts. Marine Ecology Progress Series 376:295-306

Wooldridge, Scott; Done, Terry; Berkelmans, Ray; Jones, Roger; and Marshall, Paul. 2005. Precursors for resilience in coral communities in warming climate: a belief network approach. Marine Ecology Progress Series 295:157-69

KELP FOREST TO ALGAE TURFS AND URCHIN BARRENS

2. Diagram of regime shift dynamics



3. Summary of regime shift

Kelp forests may undergo regime shifts to turf-forming algae and urchin barrens. This shift leads to loss of habitat and ecological complexity. Shifts to turf algae are related to nutrient input, while shifts to urchin barrens are related to trophic-level changes. The consequent loss of habitat complexity may affect commercially important fisheries. Managerial options include restoring biodiversity and installing wastewater treatment plants in coastal zones.

2. Description of the alternate regimes and reinforcing feedbacks

This regime shift is associated with a change in habitat in shallow marine coastal ecosystems. Three different self-reinforcing regimes can be identified:

Kelp forests are highly productive ecosystems dominated by canopy-formed algae in cold-water rocky marine coastlines. Among the biota associated with kelp forest are marine mammals, fishes, crabs, sea urchins, mollusks, other algae and epibiota (Steneck *et al.,* 2002). At least 4 trophic levels are found in kelp forests, and apex predators such as sea otters, cod, Pollock, hake, and haddock are common. These predators control lower trophic levels, and especially sea urchins, the main herbivore, are kept in low numbers. In addition, urchins are prevented from grazing in the kelp forest through the effect of kelp foliage sweeping over the rocks due to its flexibility and the force of waves (Konar & Estes, 2003).

Urchin barrens are formed where the kelp canopy has been deforested by urchins. Trophic-level cascades are responsible for urchin overabundance. Overfishing of the apex predators can leads to shifts in the dominance of consumers at lower trophic levels (Steneck *et al.*, 2004). This is been particularly observed in the case of overfishing of sea otter, cod and haddock, which have released prey populations such as urchins from their predatory controls. Large populations of urchins form grazing fronts graze down strongly on kelp forest and can survive in adverse conditions by feeding on turf-forming algae (Lauzon-Guay *et al*., 2009).

In some cases trophic-level cascades have allowed other species to reach sufficient population sizes to exert some control on urchins, for instance lobsters and crabs in the North Atlantic (Steneck *et al.,* 2002). In addition, declines in predatory fish have created a market for urchins, especially in Japan, establishing a new human induced control on the herbivore. In some cases, harvesting of urchins for this market has led to the re-establishment of kelp forest, despite urchin fishery being prohibited (Scheffer 2009; Steneck *et al.*, 2002).

Turf-forming algae may be considered another alternative stable state where opportunistic species with simple and less diverse elements dominate a seascape previously dominated by kelp, a perennial species with structurally complex community (Gorman *et al.*, 2009). The feedback is given by the ability of turf-forming algae to persist under conditions of elevated nutrients, frequently attributed to coastal urban settlements, inhibiting the recruitment of kelp species (Gorman *et al.,* 2009).

3. Drivers that precipitate the regime shift

Two key direct drivers are identified: overfishing functional groups (Steneck *et al.,* 2002; 2004) and input of nutrients (Gorman *et al.*, 2009). The latter is related to deposition of wastewater from urban settlement and agriculture in adjacent catchments. El Niño events or global warming events may generate water stratification. As consequence, nitrogen concentration declines and kelps become nitrogen limited (Steneck *et al.,* 2002). In addition pollution discharges and sedimentation may play a synergetic role as stressors. In Tasmania for example, global warming has favored the reproduction of urchins which acting in synergy with lobster fishing has reduced kelp resilience (Ling *et al.,* 2009).

4. Impacts on ecosystems and human well-being

The main ecosystem impact is the loss of habitat complexity due to kelp defoliation. Kelp is a 3 dimensional structure that offers shelter and food for many species; urchin barrens and turfs do not have such characteristic. This loss is associated with the reduction of the food web complexity and loss of functional groups (Steneck *et al.,* 2004), with varying effects on fisheries. Some valuable fish species may diminish since kelp forests provide nursery areas. However, invertebrate species such as lobster and crab have shown increases in population (Steneck *et al.*, 2002). However, the abundance of such lower-level consumers reflects an exacerbation of the "fishing down food web" effect (Pauly et al 1998). The ecosystem service impacts of algae turfs are likely to be similar to those related to coastal eutrophication. Such effects include abundance of rich-nutrient environment species as shellfish, bad odors and the associated consequences for recreational and aesthetic values.

In addition, kelps support a multimillion dollar industry of canopy-cropping for alginates (Steneck *et al.,* 2002). This product is commercially important in pharmaceutical and chemical industry.

5. Management options for preventing or reversing regime shift

Managerial options include wastewater treatment plants, reduce nutrient inputs from agriculture and urban settlements (Gorman *et al.*, 2009) and restoring biodiversity in functional groups. The abundance of predators like cod, sea otters and sheep-head through fishery controls may provide stability to kelp forest ecosystems (Steneck *et al*. 2004; 2002).

6. Links to other regime shifts

Fisheries collapse

7. **Key direct drivers of the RS**

- 7.1. Vegetation conversion and habitat fragmentation
- 7.2. Harvest and resource consumption
- 7.3. External inputs (eg fertilizers, pest control, irrigation)
- 7.4. Adoption of new technology (eg new fishing nets)
- 7.5. Infrastructure development (eg roads, pipelines)
- 7.6. Species introduction or removal
- 7.7. Disease

7.8. Soil erosion & land degradation
7.9. Environmental shocks (eg fire, floods, droughts)
7.10. Global climate change

8. **Impacts on ecosystem services**
   8.1. Provisioning services
      - Freshwater
      - Food Crops
      - Livestock
      - Fisheries
      - Wild animal and plant foods
      - Timber
      - Woodfuel
      - Other crops (eg cotton)
   8.2. Regulating services
      - Air quality regulation
      - Climate regulation
      - Water purification
      - Water regulation
      - Regulation of soil erosion
      - Pest & Disease regulation
      - Pollination
      - Natural hazard regulation
   8.3. Cultural services
      - Recreation
      - Aesthetic values
      - Knowledge and educational values
      - Spiritual and religious
   8.4. Biodiversity

9. **Impacts on Key Ecosystem Processes**
   9.1. Soil formation
   9.2. Photosynthesis
   9.3. Primary production
   9.4. Nutrient cycling
   9.5. Water cycling

10. **Impacts on Human Well-being**
   10.1. Food and nutrition
   10.2. Health (eg toxins, disease)
   10.3. Livelihoods and economic activity
   10.4. Security of housing & infrastructure
   10.5. Cultural, aesthetic and recreational values

10.6. Social conflict
10.7. No direct impact

11. **Ecosystem type in which the RS occurs**
    11.1. Marine & coastal
    11.2. Freshwater lakes & rivers
    11.3. Temperate & Boreal Forests
    11.4. Tropical Forests
    11.5. Moist savannas & woodlands
    11.6. Drylands & deserts (below ~500mm rainfall/year)
    11.7. Grasslands
    11.8. Tundra
    11.9. Polar
    11.10. Planetary

12. **Land use under which the RS occurs**
    12.1. Urban
    12.2. Small-scale subsistence crop cultivation
    12.3. Large-scale commercial crop cultivation
    12.4. Intensive livestock production (eg feedlots, dairies)
    12.5. Extensive livestock production (natural rangelands)
    12.6. Timber production
    12.7. Fisheries
    12.8. Mining
    12.9. Conservation
    12.10. Tourism
    12.11. Land use impacts are primarily off-site (e.g. dead zones in the ocean caused by fertilizer use in the continental interior; in these cases, also indicate the relevant land uses above)

13. **Typical spatial scale at which RS occurs**
    13.1. Local/landscape (e.g. lake, catchment, community)
    13.2. Sub-continental/regional (e.g. southern Africa, Amazon basin)
    (actual RS mechanism occurs at the regional scale OR cumulative impact/extent of local-scale RS is regional in scale)
    13.3. Global

14. **Typical time scale over which RS occurs**
    14.1. Weeks
    14.2. Months
    14.3. Years
    14.4. Decades
    14.5. Centuries

14.6.Unknown

15. **Reversibility of RS**
    15.1.Irreversible (on 100 year time scale)
    15.2.Hysteretic
    15.3.Readily reversible
    15.4.Unknown

16. **Confidence: Existence of RS**
    16.1.Speculative – Regime shift has been proposed, but little evidence as yet
    16.2. Contested – Reasonable evidence both for and against the existence of RS
    16.3. Well established – Wide agreement in the literature that the RS exists

17. **Confidence: Mechanism underlying RS**
    17.1.Speculative – Mechanism has been proposed, but little evidence as yet
    17.2.Contested – Multiple proposed mechanisms, reasonable evidence both for and against different mechanisms
    17.3. Well established – Wide agreement on the underlying mechanism

18. **Evidence**
    18.1.Models
    18.2.Paleo-observation
    18.3.Contemporary observations
    18.4.Experiments
    18.5.Other

19. Contributors

Juan Carlos Rocha
Stockholm Resilience Centre.
juancarlosrochag@gmail.com

Oonsie Biggs

20. Key References

References cited in the paragraph descriptions and other key references

Gorman, D; Russell, B.D; and Conell, S.D. 2009. Land-to-sea connectivity: linking human-derived terrestrial subsidies to subtidal habitat change on open rocky coasts. Ecological Applications 19 (5) pp. 1114-1126

Konar, B; and Estes, J. 2003.The stability of boundary regions between kelp beds and deforested areas. Ecology 84 (1) pp. 174-185

Lauzon-Guay, J; Scheibling R.E; and Barbeau, M.A. 2009. Modelling phase shifts in a rocky subtidal ecosystem. Mar Ecol-Prog Ser 375 pp. 25-39

Ling SD, Johnson CR, Frusher SD, Ridgway KR. 2009. Overfishing reduces resilience of kelp beds to climate-driven catastrophic phase shift. P Natl Acad Sci Usa 106 (52) pp. 22341-22345

Pauly D., V. Christensen, J. Dalsgaard, R. Froese, and F. Torres, Jr. 1998. Fishing Down Marine Food Webs. *Science*, **279:**860-863.

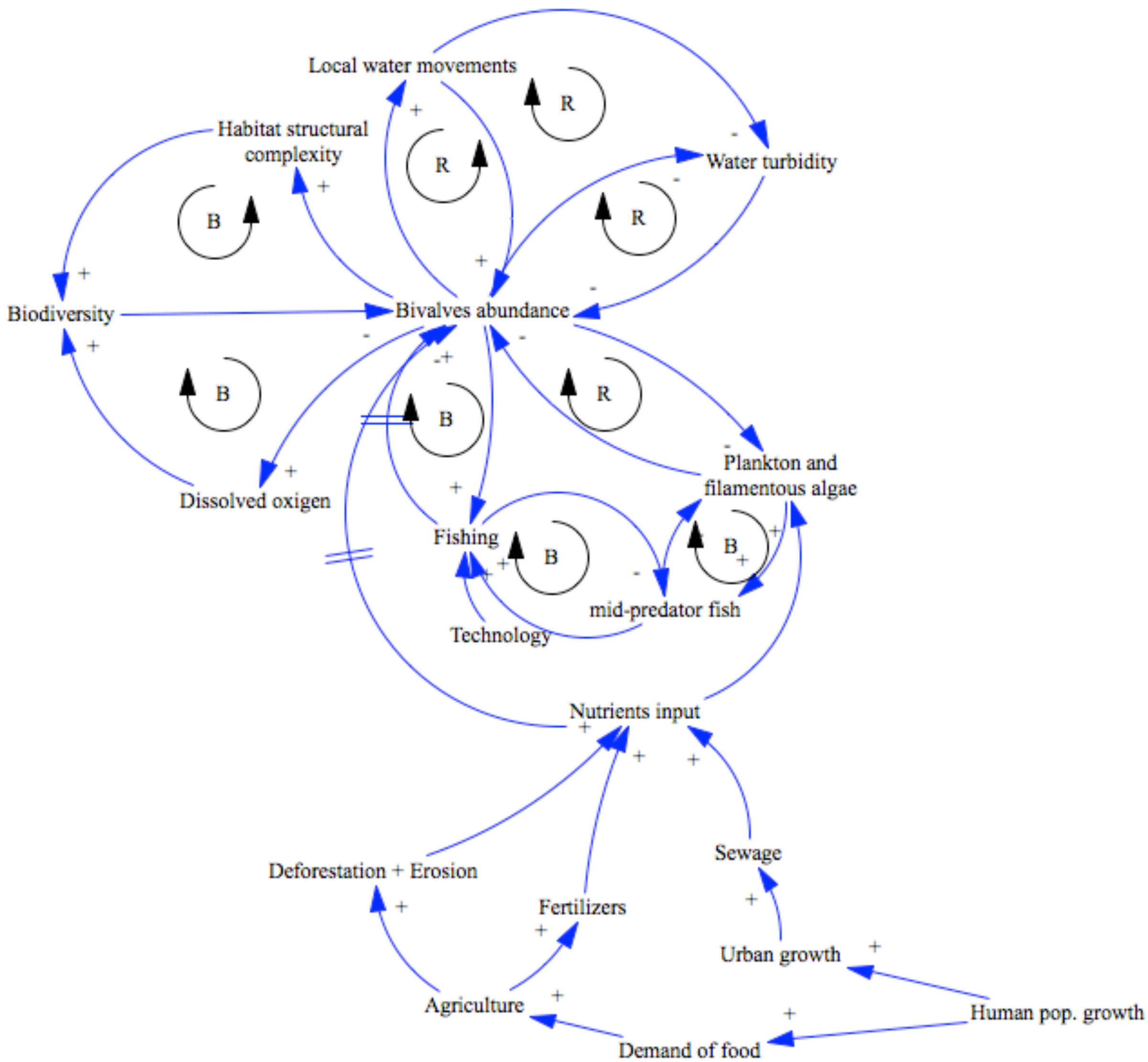
Scheffer, M. 2009. Critical Transitions in Nature and Society. Princenton Studies in Complexity. 384p

Steneck, R; Graham, M; bourque, B; Corbett, D; Erlandson, J; Estes, J; Tegner, M. 2002. Kelp forest ecosystems: biodiversity, stability, resilience and future. Environ. Conserv. 29 (4) pp. 436-459

Steneck, R; Vavrinec, J; and Leland, A. 2004. Accelerating trophic-level dysfunction in kelp forest ecosystems of the western North Atlantic. Ecosystems 7 (4) pp. 323-332

BIVALVE COLLAPSE

2: Diagrams/Photos of regime shift dynamics



3: Summary of regime shift

Bivalvia is a class of molluscs containing over 30,000 species including scallops, clams oysters and mussels. Bivalve molluscs are often referred to as "ecosystem engineers" because they affect the physical and hydrodynamic structures of the ecosystems they occupy. They live on the sediment surface, where they form reefs that provide increased surface area and habitat for a variety of species. They filter nutrients from the pelagic zone and transfer it to the benthic zone, maintaining the system in a clear water state. If bivalve populations are not sufficiently abundant to carry out this function, the state of the ecosystem can shift to a turbid water state. The main driver of this shift is direct anthropogenic over-harvesting of the bivalves.

4: Description of the alternate regimes and reinforcing feedbacks

Bivalve molluscs play an important role in aquatic ecosystems by filtering and sequestering nutrients. When bivalve abundance changes, it can have substantial ecosystem impacts, creating two different, self-reinforcing regimes.

The high bivalve mollusc abundance regime

When aquatic ecosystems have high bivalve mollusc abundance, the reefs are large and shallow, nearing the water's surface. The filtering activity of the bivalves results in clear water with high levels of dissolved oxygen. Plankton populations are limited in these conditions. Large, shallow bivalve mollusc reefs encourage biodiversity by providing habitat and filtering nutrients. The bivalves themselves operate as reinforcing feedbacks in that their abundance ensures sufficient filtration to maintain this clear water regime. The clear water in turn reinforces bivalve abundance by maintaining hydrodynamics that are conducive to bivalve health (Scheffer, 2009).

The low bivalve mollusc abundance regime

When aquatic ecosystems have low bivlave mollusc abundance, the reefs are small and deep. Water is turbid, with low levels of dissolved oxygen. Plankton and filamentous algae flourish under these conditions. Poor reef size and water filtration limit biodiversity. The low bivalve abundance state is reinforced as bivalve health and fecundity is weakened by turbid water conditions. The turbid water conditions are in turn reinforced by low bivalve abundance (Powell et al, 2008; Weijerman et al, 2005).

5: Drivers that precipitate the regime shift

Mechanized anthropogenic over-harvesting of bivalve molluscs is the main driver of the shift from high to low abundance (Thrush, 2002). High inputs of nutrients from agricultural or urban sources can act as a slow driver that weakens bivalve health by creating plankton blooms that the bivalves are insufficient to filter. When the organic matter from these blooms decomposes, oxygen is depleted from the system, which further weakens the health of bivalves. A system shock can come in the form of bivalve disease (Powell, 2008). When populations are weakened by eutrophication and anoxia, they become physiologically susceptible to diseases which can rapidly devastate remaining populations (Leniham et al, 1999).

6: Impacts on ecosystems and human well-being

The loss of abundant bivalve mollusc reefs threatens diverse ecosystem services. The most direct impact is the loss of valuable shellfisheries. When the filtering service provided by bivalves is lost from urbanized estuaries, it can necessitate the installation of costly synthetic water filtration technology (Gren, 2009). The loss of bivalve nutrient filtration can lead to other regime shifts, such as eutrophication and anoxia, which can result in aquatic dead zones. The loss of bivalve habitat structure leads to lower species abundances, and to declines in species richness (Airoldi, 2008). Both structural and functional biodiversity is threatened by loss of bivalve abundance, with far reaching effects on marine ecosystems and human ability to exploit such systems (Worm, 2006).

7: Management options for preventing or reversing regime shift

The main option exercised for preventing or reversing a regime shift regarding bivalve abundance is to import bivalve molluscs from another region for aquaculture (Van Del Koppel et al, 2009). Another practice commonly used is to hang bivalves from the surface or build artificial reefs to elevate bivalves in order to avoid the hypoxic conditions in deeper water. (Carlsson et al, 2009).

Estuaries are the world's most degraded marine ecosystems, receiving land-based pollution from crop cultivation and urbanization, and suffering from anthropogenic over-harvesting (Lotze et al, 2006). The resulting problems are complex, impacting bivalve health and fecundity as well as many other species, with far reaching implications in both biological and social domains.

Experience has shown that management focused on one species or problem tends to be ineffective. Newer research stresses the need to address natural resources as part of complex social-ecological systems, often with long histories of human exploitation (Jackson et al, 2001). Rather than addressing problems on a species-by-species basis, multi -species management has shown to have synergistic effects. For example, in chesapeake bay, fisheries management looks at oyster, blue crab, striped bass and shad together (Boesch, 2004).

Taking this approach further, Ecosystem-based fishery management efforts focus on recognizing interactions between multiple species and environmental stressors, such as low dissolved oxygen levels. Success is measured by the degree to which management efforts include ecosystem-based approaches, rather than by an assessment of fishing stocks (Lotze, 2006).

Links to other regime shifts
Eutrophication
Anoxia

Bivalve molluscs can act as buffers to delay the eutrophication and anoxia regime shifts. Eutrophication and anoxia are drivers for the bivalve low abundance shift.

List other regime shifts that may be triggered by or that may trigger the current regime shift.

The following fields serve as summaries of the details captured in 3-6, their main purpose being to enable searching and organization of the database.

Key direct drivers of the RS

Vegetation conversion and habitat fragmentation
Harvest and resource consumption
External inputs (eg fertilizers, pest control, irrigation)
Adoption of new technology (eg new fishing nets)
Infrastructure development (eg roads, pipelines)
Species introduction or removal
Disease
Soil erosion & land degradation
Environmental shocks (eg fire, floods, droughts)
Global climate change

Impacts on ecosystem services

Provisioning services

- Freshwater
- Food Crops
- Livestock
- Fisheries
- Wild animal and plant foods
- Timber
- Woodfuel
- Other crops (eg cotton)

Regulating services

- Air quality regulation
- Climate regulation
- Water purification
- Water regulation
- Regulation of soil erosion
- Pest & Disease regulation
- Pollination
- Natural hazard regulation

Cultural services

- Recreation
- Aesthetic values
- Knowledge and educational values
- Spiritual and religious

Biodiversity

Impacts on Key Ecosystem Processes

Soil formation

Photosynthesis
Primary production
Nutrient cycling
Water cycling

Impacts on Human Well-being
Food and nutrition
Health (eg toxins, disease)
Livelihoods and economic activity
Security of housing & infrastructure
Cultural, aesthetic and recreational values
Social conflict
No direct impact

Ecosystem type in which the RS occurs
Marine & coastal
Freshwater lakes & rivers
Temperate & Boreal Forests
Tropical Forests
Moist savannas & woodlands
Drylands & deserts (below ~500mm rainfall/year)
Grasslands
Tundra
Polar
Planetary

Land use under which the RS occurs
Urban
Small-scale subsistence crop cultivation
Large-scale commercial crop cultivation
Intensive livestock production (eg feedlots, dairies)
Extensive livestock production (natural rangelands)
Timber production
Fisheries
Mining
Conservation
Tourism
Land use impacts are primarily off-site (e.g. dead zones in the ocean caused by fertilizer use in the continental interior; in these cases, also indicate the relevant land uses above)

Typical spatial scale at which RS occurs
Local/landscape (e.g. lake, catchment, community)
Sub-continental/regional (e.g. southern Africa, Amazon basin)

(actual RS mechanism occurs at the regional scale OR cumulative impact/extent of local-scale RS is regional in scale)

Global

Typical time scale over which RS occurs

Weeks
Months
Years
Decades
Centuries
Unknown

Reversibility of RS

Irreversible (on 100 year time scale)
Hysteretic
Readily reversible
Unknown

Confidence: Existence of RS

Speculative – Regime shift has been proposed, but little evidence as yet
Contested – Reasonable evidence both for and against the existence of RS
Well established – Wide agreement in the literature that the RS exists

Confidence: Mechanism underlying RS

Speculative – Mechanism has been proposed, but little evidence as yet
Contested – Multiple proposed mechanisms, reasonable evidence both for and against different mechanisms
Well established – Wide agreement on the underlying mechanism

Evidence

Models
Paleo-observation
Contemporary observations
Experiments
Other

<u>Contributors</u>

Christine Hammond, Stockholm Resilience Centre

Key References

Airoldi, L., Balata, B. Beck, M.W. 2008 The Grey Zone: Relationships between habitat loss and marine diversity. Journal of experimental marine biology and ecology: 366 pp. 8-15

Boesch, D.F. 2004. Scientific requirements for ecosystem-based management in the restoration of Chesapeake Bay and Coastal Louisiana. Ecological Engineering. 26 (1) pp 6-26

Carlsson, M.S., Holmer, M., Petersen, J.K. 2009 Seasonal and spatial variations of benthic impacts of mussel longline farming in a eutrophic Danish Fjord, Limfjorden. Journal of Shellfish Research. 28 (4) pp 791-801

Eriksson, B.D.K.H, Van Del Koppel, J., Ter Neer, H., Piersma, T., Olff, H., Olsen, J.L. 2009. A human-driven regime shift through the loss of ecosystem engineers: consequences for the trophic structure and recovery potential of the Wadden Sea ecosystem. NWO

Gren, I., Lindahl, O., Lindqvist, M. 2009 Values of Mussel farming for combating eutrophication: An application to the Baltic Sea. Ecological Engineering. In Press: doi:10.1016/j.ecoleng.2008.12.033

Jackson, J; Kirby, M; Berger, W; Bjorndal, K; Botsford, L; Bourque, B; Bradbury, R; Cooke, R; Erlandson, J; Estes, J; Hughes, T; Kidwell, S; Lange, C; Lenihan, H; Pandofi, J; Peterson, C; Steneck, R; Tegner, M; and Warner, R. 2001. Historical Overfishing and the Recent Collapse of Coastal Ecosystems. Science. 293 pp. 639-637

Leniham, H.S., Micheli, F., SHelton, S.W., Peterson, C.H. 1999 The influence of multiple environmental stressors on susceptibility to parasites: An experimental determination with oysters. Limnology and Oceanography: 44 (3) pp. 910-924

Loo, L.O. ,and R.Rosenber., 1989. Bivalve suspension-feeding dynamics and benthic-pelagic coupling in an eutrophicated marine bay. J. Exp. Mar. Biol. Ecol. 130: pp. 253-276

Lotze H. K., et Lenihan, H.S., Bourque, B., Bradbury, R.H., Cooke, R.G., Kay, M.C., Kidwell, S.M., Kirby, M.X., Peterson, C.H., Jackson, J.B.C. 2006 Depletion, degradation and recovery potential of estuaries and coastal seas. Science 312 pp. 1806–1809.

Norroko, A., Hewitt, J., Thrush, S., Funnell, G. 2006 Conditional outcomes of facilitation by a habitat-modifying subtidal bivalve. Ecology 87(1) pp. 226-234

Powell, EN, Ashton-Alcox, K.A, Kraeuter JN, Ford SE, Bushek D. Long-term trends in oyster population dynamics in Delaware Bay: Regime shifts and response to disease. J Shellfish Res (2008) vol. 27 (4) pp. 729-755

Scheffer, M. 2009. Critical Transitions in Nature and Society. Princeton Studies in Complexity pp. 207-208

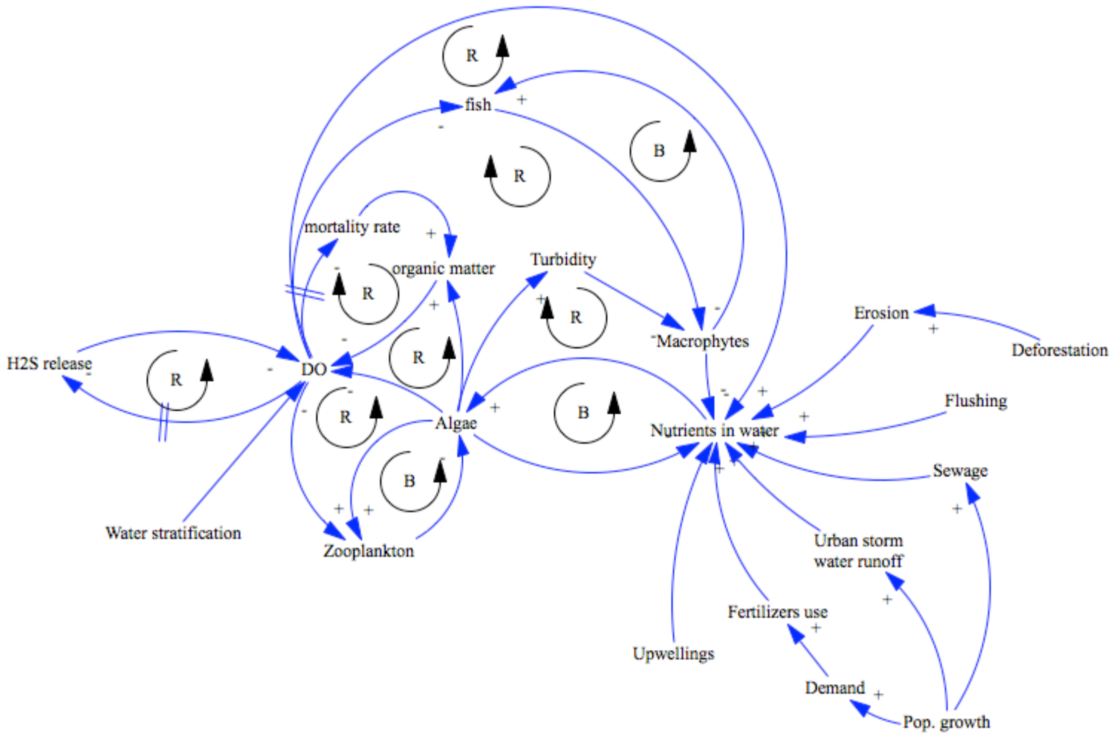
Thrush, S.F. and Paul K. Dayton. 2002 Disturbance to marine benthic habitats by trawling and dredging: Implications for marine biodiversity. Annu. Rev. Ecol. Syst. 33 pp. 449-473

Weijerman, M., Lindeboom, H., Zuur, A. Regime shifts in marine ecosystems of the North Sea and Wadden Sea 2005 Mar Ecol Prog Ser 298 pp. 21-39

Worm, B., Barbier, E., Beaumont, N., Duffy, E., Folke, C., Halpern, B.S., jackson, J.B.C., Lotze, H.k., Micheli, F., Palumbi, S.R., Sala, E., Selkoe, K.A., Stachowicz, J.J., Watson, R. 2006 Impacts of biodiversity loss on ecosystem services. Science: 314 pp. 787-790

HYPOXIA: Dead zones in aquatic ecosystems

2. Diagram



3. Summary

The critical variable in the hypoxia regime shift is dissolved oxygen in the water (DO). Two different self-reinforcing regimes can be identified: normoxia and hypoxia. Hypoxia is typically associated with eutrophication, and related to excess nutrient inputs from fertilizers or untreated sewage. Management options include the reduction of nutrient inputs i.e. by closing the nutrient cycle in agricultural systems and through waste-water treatment.

4. Description of the regime shift dynamics

The hypoxia regime shift involves a radical change in oxygen concentration in aquatic ecosystems such as rivers, lakes and marine ecosystems. Two different self-reinforcing regimes can be identified (Diaz & Rosenberg 2008):

Normoxia: This regime is characterized by normal levels of dissolved oxygen, typically around 8 ml per litre. Most aquatic organisms are adapted to survive under these conditions. Particularly important are the benthic organisms. Benthos are a community of organisms which live in sedimentary environments at the bottom of water bodies. They constitute an important key functional group (scavengers and detritivores) in the food web responsible for the decay of dead matter. Macrobenthos are particularly important because they facilitate bioturbation processes - in other words, they displace and mix particles facilitating chemical exchange between sediments and the water column. This allows the sediments to “capture” phosphorous and nitrogen from the water column. Phosphorous and nitrogen are associated with excess fertilizer runoff, and promote algal blooms (eutrophication), which in turn lead to reduced oxygen levels. By removing phosphorous and nitrogen from the water column, bioturbation therefore reduces algal growth and helps ensure that the water remains oxygenated and suitable for the survival of benthos - creating a reinforcing feedback that maintains normoxia conditions.

Hypoxia: The hypoxic state is reached when dissolved oxygen level falls below 2 ml per liter (Diaz & Rosenberg 2008). Hypoxia is associated with so-called “dead zones”. These are areas where dissolved oxygen levels are so low that most life is not able to persist and only very few specialized microorganisms survive. The main anthropogenic driver of hypoxia is the delivery of large quantities of nutrients from agricultural systems, leading to eutrophication. Eutrophication is associated with algal blooms in the upper water layers, which leads to increased deposition of organic matter in the deeper water layers. This promotes the growth of microbes that decompose the organic matter, and their respiration in turn consumes oxygen. When combined with features such as semi-enclosed hydrogeomorphology and water-column stratification that restrict water exchange and reoxygenation of the deeper water layers, eutrophication is associated with hypoxia events (Diaz & Rosenberg 2008). Hypoxia can also occur under natural conditions, such as coastal upwelling, that lead to nutrient enrichment along continental margins.

The hypoxic regime is maintained by a change in feedback related to the benthic fauna. Macrobenthos cannot survive under hypoxic conditions; DO levels below 0.5 ml per litre are typically associated with mass mortality of benthic animals. Loss of the benthic fauna alters sedimentary habitats through the disruption of nitrification and denitrification processes. Instead of nitrogen being removed as N_2, ammonia and ammonium together with phosphorous are released from the sediments. This further stimulates the growth of algae, the deposition of organic matter, the growth of microbes, and the depletion of oxygen – i.e. creates a reinforcing feedback that maintains the hypoxic regime (Diaz & Rosenberg 2008). Physical processes that stratify the water column make the oxygenation of water even more difficult and exacerbate the hypoxic conditions.

The severity and persistence of hypoxic conditions varies. Episodic oxygen depletion represents 17% of known hypoxia cases, and occurs infrequently with several years sometimes elapsing between events. Episodic oxygen depletion is the first signal that a system has reached a critical point of eutrophication, which in combination with physical processes that stratify the water column, tips the system into hypoxic conditions (Diaz & Rosenberg 2008). Seasonal hypoxia tends to occur periodically during the summer, after algal spring blooms have sunk to the bottom and are being decomposed. It lasts from days to weeks, represents half of the known dead zones, and typically abates in the autumn (Diaz & Rosenberg 2008). Boom-and-bust cycles of animal populations are frequent. Persistent hypoxia occurs when hypoxia becomes persistent due to the build-up of organic matter in the sediments over time, particularly in systems prone to persistent stratification. Persistent hypoxia accounts for 8% of reported hypoxia cases. Anoxia occurs when

DO levels fall below 0.2 ml per litre. The accumulation of organic matter is exacerbated, and hydrogen sulphide (H_2S) is released due to microbial metabolism.

The fast variable in the hypoxia regime shift is DO, and can also include faunal composition. The slow variables are the accumulation of nutrients, mainly phosphorous and nitrogen in the water column. A positive feedback loop is created when hypoxic conditions lead to phosphorus release from the sediments. In addition, available nitrogen increases in the form of ammonia and ammonium in absence of macrobenthos. Stratification and flushing are important external drivers determined mainly by climate variation. Increased variability due to climate change could therefore have an important impact on the extent and severity of hypoxia.

5. Impact on ecosystems, ecosystem services and human well-being

Dead zones due to hypoxia have been reported in more than 400 systems affecting more than 245,000 square kilometres and including important fisheries such as the Baltic Sea, Kattegat, Black Sea, Gulf of Mexico, and East China Sea (Diaz & Rosenberg 2008). A major impact on ecosystems is a change in the flux of matter and energy through trophic levels. Consequently, fisheries and hence ecosystem services such as food production are affected. For example, Diaz & Rosenberg (2008) report that biomass in the Baltic Sea has been reduced by approximately 264,000 metric tons of carbon due to hypoxic conditions. Assuming that ~40% of benthic energy passes up the food chain, 106,000 metric tons of carbon of food energy for fisheries has been lost (Diaz & Rosenberg 2008). This implies a reduction in yields and consequent impact on employment in fisheries communities. Another example of such effects is the lobster fishery collapse in Norway (Diaz & Rosenberg 2008).

6. Management options for preventing and reversing the regime shift

Since one of the main drivers of hypoxia is eutrophication, Diaz & Rosenberg (2008) recommend managing the input of fertilizers on agricultural land. They recognize the necessity of developing new methods to close the nutrient cycle on farms, in order to avoid the drainage of nutrients to water sources. Nutrient reductions can also be achieved relatively cost-efficiently by improving waste-water treatment system in regions where this is applicable (e.g. Baltic Sea).

Only 4% of the reported cases of hypoxia have shown improvement, principally due to the reduction of organic and nutrient loading, stratification strength, and freshwater runoff (Diaz & Rosenberg 2008). Managers could take advantage of windows of opportunity provided by these variables. For example, in the Baltic Sea the stratification of the water column is determined by input of saltwater from the North Sea (Conley *et al.* 2009). A policy of nutrient load reduction would therefore be more effective in years when saltwater input is low and it is a particularly rainy year. While nutrient loading is largely periodic and rain dependent, stratification and freshwater runoff rely more on physical processes and climate variability. Finally, it has been suggested that an appropriate goal is the reduction of nutrient loads to the level of the mid-1900s (Diaz & Rosenberg 2008).

7. Related regimes

Lake eutrophication, oceanic eutrophication, fisheries collapse

8. Key direct drivers of the RS
    1. Habitat conversion or fragmentation
    2. Harvest and resource consumption
    3. External inputs (eg fertilizers, pest control, irrigation)
    4. Adoption of new technology (eg new fishing nets)
    5. Infrastructure development (eg roads, pipelines)
    6. Species introduction or removal
    7. Disease
    8. Soil erosion & land degradation
    9. Environmental shocks (eg fire, floods, droughts)
    10. Global climate change

9. Impacts on ecosystem services
    - 9.1. Provisioning services:
        - 9.1.1. Freshwater
        - 9.1.2. Food Crops
        - 9.1.3. Livestock
        - 9.1.4. Fisheries
        - 9.1.5. Wild animal and plant foods
        - 9.1.6. Timber
        - 9.1.7. Woodfuel
        - 9.1.8. Other crops (eg cotton)
    - 9.2. Regulating services
        - 9.2.1. Air quality regulation
        - 9.2.2. Climate regulation
        - 9.2.3. Water purification
        - 9.2.4. Water regulation
        - 9.2.5. Regulation of soil erosion
        - 9.2.6. Pest & Disease regulation
        - 9.2.7. Pollination
        - 9.2.8. Natural hazard regulation
    - 9.3. Cultural services
        - 9.3.1. Recreation
        - 9.3.2. Aesthetic values
        - 9.3.3. Knowledge and educational values
        - 9.3.4. Spiritual and religious
    - 9.4. Biodiversity

10. Impacts on Key Ecosystem Processes
    - 10.1. Soil formation
    - 10.2. Photosynthesis

- 10.3. Primary production
- 10.4. Nutrient cycling
- 10.5. Water cycling

11. Impacts on Human Well-being
    - 11.1. Food and nutrition
    - 11.2. Health (eg toxins, disease)
    - 11.3. Livelihoods and economic activity
    - 11.4. Security of housing & infrastructure
    - 11.5. Social conflict

12. Ecosystem type in which the RS occurs
    - 12.1. Marine & coastal
    - 12.2. Freshwater lakes & rivers
    - 12.3. Forests
    - 12.4. Savannas, Grasslands & Drylands
    - 12.5. Tundra & Polar
    - 12.6. Planetary

13. Land use drivers of the regime shift
    - 13.1. Urban
    - 13.2. Small-scale subsistence crop cultivation
    - 13.3. Large-scale commercial crop cultivation
    - 13.4. Intensive livestock production (eg feedlots, dairies)
    - 13.5. Extensive livestock production (natural rangelands)
    - 13.6. Timber production
    - 13.7. Fisheries
    - 13.8. Mining
    - 13.9. Conservation
    - 13.10. Tourism
    - 13.11. Land use impacts are primarily off-site (e.g. dead zones in the ocean caused by fertilizer use in the continental interior; in these cases, also indicate the relevant land uses above)

14. Typical spatial scale at which RS occurs
    - 14.1. Local/landscape (e.g. lake, catchment, community)
    - 14.2. Sub-continental/regional (e.g. southern Africa, Amazon basin)
    - 14.3. Global

15. Typical time scale over which RS occurs
    - 15.1. Weeks
    - 15.2. Years
    - 15.3. Decades

15.4. Centuries
15.5. Unknown

16. Reversibility of RS
    16.1. Irreversible
    16.2. Hysteretic
    16.3. Readily reversible
    16.4. Unknown

17. Confidence (IPCC language)
    17.1. Speculative – Regime shift has been proposed, but little evidence as yet
    17.2. Contested – Reasonable evidence both for and against the existence of RS
    17.3. Well established – Wide agreement in the literature that the RS exists

18. Evidence
    18.1. Models
    18.2. Paleo-observation
    18.3. Contemporary observations
    18.4. Other

19. Contributor and Reviewer

Juan Carlos Rocha
Stockholm Resilience Centre
juancarlosrochag@gmail.com
Susa Niiraren
Baltic Nest Institute
sniir@mbox.su.se

20. Last updated: September 14, 2009

21. Key References

Díaz, Robert and Rosenberg, Rutger. 2008. Spreading Dead Zones and Consequences for Marine Ecosystems. Science **321**: 926-29

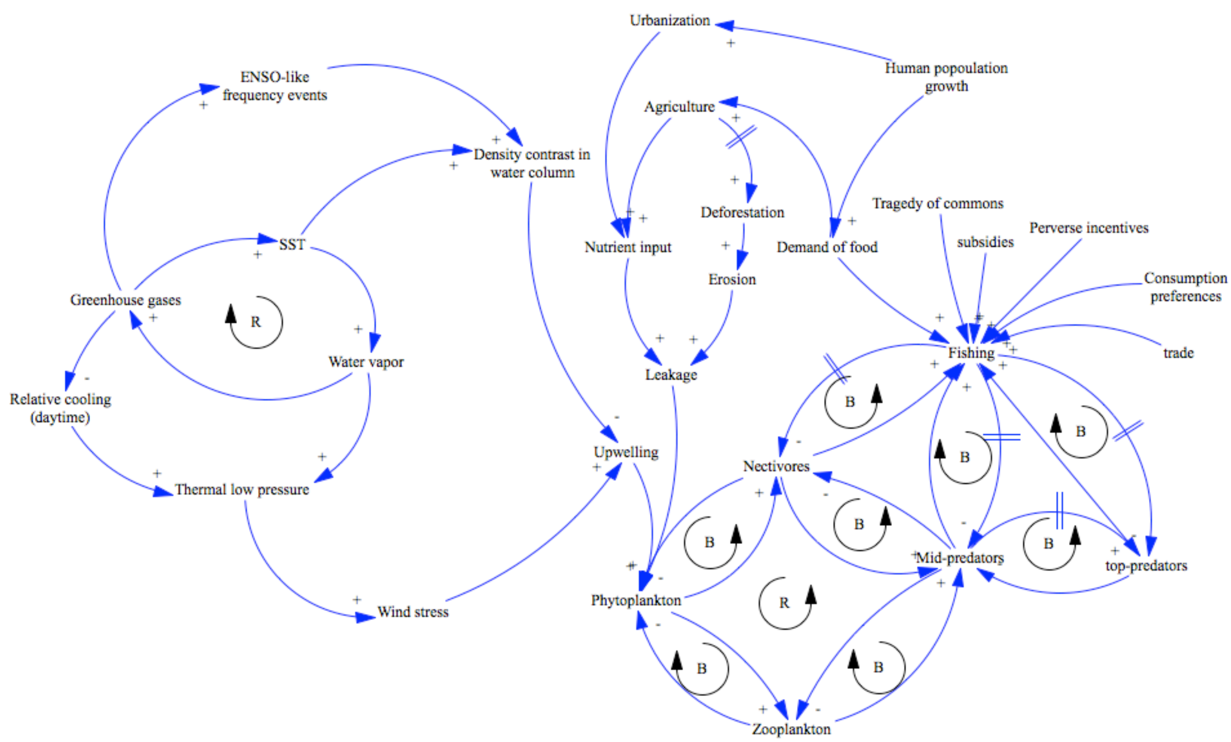
Conley, D; .Björck, S; Bonsdorff, E; Cartensen, J; Destouni, G; Gustafsson, B.G; Hietanene, S; Kortekaas, M; Kuosa, H; Meier, H.E.M; Mueller-Karulis, B; Nordberg, K; Norkko, A; Nuernberg, G; Pitkanen, H; Rabalais, N.N; Rosenberg, R; Savchuk, O.P; Slomp, C.P; Voss, M; Wulff, F; Zillen, L. 2009. Hypoxia-Related Processes in the Baltic Sea. Environ Sci Technol 43(10); 3412-3420

COLLAPSE OF COMMERCIAL FISHERIES

1. Regime shift name

Collapse of commercial fisheries

2. Diagram of regime shift dynamics



3. Summary of regime shift

A fishery collapses when the structure of the marine community (its species composition) changes radically, locking the system into a regime where high valued commercial species cannot recover.. These dynamics are usually characterized by cascading effects across multiple trophic levels. Two main types of anthropogenic forces shape the collapse of commercial fisheries. Overfishing is the main top-down driver, and is associated with indirect drivers like new markets, trade facilities and technology improvements. Bottom-up drivers are produced by anthropogenic and natural climate change, mainly by changing the intensity and frequency of upwellings; in other words, the changing the energy input into marine food webs, and hence their productivity. Environmental factors such as diseases, ocean current patterns, winds and temperature variation can act as synergistic factors triggering collapses. The collapse of a commercial fishery can have substantial economic impacts.

4. Description of the alternate regimes and reinforcing feedbacks

A fishery collapses when the abundance of a high-valued commercial species becomes substantially depleted. It is usually associated with a substantial and persistent change in the structure of the marine community (its species composition and relative abundance). Commercial species are often predatory fish such as tuna that feed at the top of the food web. When the stock of commercial species decreases or even disappears other species, often competitors, may fill the empty niche. In the absence of competitors, prey populations may expand dramatically, with substantial impacts on marine food webs. In some cases commercial species might be favored by loss of top predators. However, in time, fishing effort may shift to focus on the newly abundant prey populations. This phenomenon is known as fishing down the food web (Pauly et al. 1998). In several cases where fishery pressure has been removed, stocks never came back to productive levels (e.g. Ainley and Blight 2009, Kirby et al. 2009), suggesting that the system has become locked into an alternate regime.

Despite evidence from some well documented cases, fisheries collapse remains a controversial issue (e.g., Hilborn 2007, Litzow and Urban 2009). Before describing the feedbacks which may lead to the different regimes, it worth noting why fishery collapses are controversial. Time series for most fisheries are only available from 1950, a time when marine ecosystems were seriously affected by flourishing industrial fishing (Ainley and Blight 2009), and some stocks had already been seriously depleted, especially those of large marine vertebrates like whales, manatees, crocodiles, seals, swordfish, sharks and rays (Jackson et al. 2001). The "natural" abundance and structure of fisheries, and whether or not they are overfished cannot be explained by recent observation alone (Jackson 2008). In addition, two important aspects of marine biology make fishery dynamics especially difficult to track. First, ecological diversity among trophic levels generate a delay between the impact of commercial fishing and the response. Functional group diversity delays the effect of a particular stock collapse on the marine food web until the whole functional group becomes ecologically extinct (Jackson et al. 2001). Second, depletion is more often perceived in K-selected life-history species (Ainley and Blight 2009), while fast growth/recovery typical of r-selected life-history species induce misperceptions of abundance. In other words, the collapse is masked by fast recovery dynamics where abundance is not a suitable response variable to depletion (Rocha unpublished).

The alternate regimes are as follows:

High abundance of a commercial fish species. In this regime the commercial fish species (often a top predator) is common and the fishery is highly productive. The regime is often also characterized by an intermediate input of nutrients that maintain relatively stable primary production

Low abundance of the commercial fish species. This regime is characterized by a substantially reduced abundance of the commercial fish species. In cases where the ecological function performed by the commercial fish species cannot be replaced by another species, it can lead to trophic cascades that lead to an overabundance of plantivorous fish or primary producers such as seagrass, macroalgae, sponge or phytoplankton (Jackson et al. 2001).

The alternate regimes are best thought of as different food web structures. The feedback mechanisms maintaining each regime operate at three different levels: depensation or Allée effects at the population level; food web regulation at the community level; and climate and ocean interactions at the regional/global level.

Depensation

Depensation refers to a situation where a decrease in the breeding population (mature individuals) leads to reduced survival and production of eggs or offspring. Depensation can result from the reduced likelihood of finding a mate when populations become low, or because of increased predation of juveniles when for instance average group size declines. When the population falls below a critical level this process can trigger a sustained decline in the population, or keep it stuck at a low level, even if fishing pressure is removed (Carpenter 2003). When the population drops below a certain threshold, it may in addition trigger changes in food webs, which can further reinforce the low abundance regime.

Food web regulation mechanisms: trophic cascades

When a commercial fish population becomes substantially reduced, it may be replaced by a competitor species that performs the same ecological role. However, if it is not replaced substantial changes in the food web may occur. If the commercial fish species is a fish predator, a drastic decrease in its abundance can lead to an explosion in the fish species that form its prey.

In some cases these prey species feed on the juveniles of their predators - e.g., sprat and cod in the Baltic Sea (Mollmann et al. 2009). A dramatic increase in the prey population can therefore lead to a much reduced survival rate of the juvenile predators. Once the system becomes locked in this regime, it may be very difficult for the predator population to recover even if fishing pressure is removed, because very few juvenile reach maturity. This in turn means that the prey population remains large because the adult predator population is too small to substantially impact on the prey population. In this case, the feedback loop is given by predatory interactions.

A second mechanism related to food web dynamics is that when food web structure is modified by top-down or bottom-up forces, species might change dietary preferences in order to adapt to new conditions. However, the over abundance of by-prey-competitors following a stock decline might keep the population unresponsive to fishing removal. In this case the positive feedback loop is given by competence interactions. For both mechanisms, nutrient input, climate and fishing are drivers that might generate pulse-like responses where trophic controls are escaped (Scheffer et al. 2008).

Climate ocean interactions

Another set of mechanisms that may reinforce a low abundance regime of a commercial fish species are climate ocean interactions which influence marine food webs through bottom-up effects. Global warming, both natural and anthropogenic, is expected to increase sea surface temperature (SST) and lead to more frequent ENSO events. An increasing frequency and intensity of warm events accentuates the density contrast in the water column, inhibiting nutrient exchange through vertical mixing (Behrenfeld et al. 2006), and thereby reducing the productivity of marine food webs. Roughly half the biosphere's net primary production is synthesized by phytoplankton in the oceans. These microscopic plants daily fix more than a hundred million tons of carbon dioxide, which in turn supports marine food webs that consume the total phytoplankton biomass every two to six days (Behrenfeld et al. 2006). Hence, inhibited mixing due to an increase in SST may substantially reduce fishery productivity by directly affecting net oceanic primary production. This phenomena has already been observed in the South American Pacific coast through satellite measurements of chlorophyll production during warm events (Behrenfeld et al. 2006).

In contrast, a parallel mechanism involving atmospheric dynamics may explain an increase in upwellings, although not necessarily an increase in fisheries productivity (Bakun et al. 2010). Increased temperatures associated with climate change promote the release of water vapor generating higher thermal low pressure cells. In other words, the difference in temperature between the air over the continental shelf and the air over the ocean increases. This physical difference increases wind stress perpendicular to the coast which in turns generates more intense upwelling (Bakun et al. 2010). However, it does not necessarily translate to higher biological productivity. In fact, nutrient-enriched food webs may become trapped in states where phytoplankton is overabundant and less mobile zooplanktivores like jellyfish (medusas) becomes their main predatory control.

5. Drivers that precipitate the regime shift

There are two key direct drivers of fisheries collapse: overfishing as a top-down disturbance, and the change in nutrients input as a bottom-up disturbance. However, the indirect drivers that explain overfishing and changes in nutrient input interact in synergistic ways, making their identification a challenging process (Kirby et al. 2009).

Overfishing is the most common cause of fisheries collapse: fishermen exploit the fish stock faster than it can recover, and once it is reduced beyond a certain level depensation and trophic cascade processes come into play that make recovery very difficult even if the fishing pressure is removed. Drivers of overfishing are related to new markets, globalization of the economy (hence, trade facilities) and technology improvements (Berkes 2006). In addition, market failures or inefficient markets can exacerbate the collapse of fisheries . Market failures are present when the cost of producing the commodity (fish) does not equal the social benefits. Market failures are present for several reasons. First, many fisheries are common pool resources (CPR), making it very difficult to control who uses the resource, and very difficult to transfer the right to do so (Ostrom 1990). Second, some groups can have more market power than others leading to imperfect competition, such as monopolies or subsidies (Hassan et al. 2005). Lastly, in small scale fisheries the loss of traditional ecological knowledge can aggravate market failures because fisherman cannot perceive and properly interpret the signals of change in ecosystems (Crona 2006). Fishermen and managers are therefore prone to misperception of feedbacks when designing fisheries management policy (Moxnes 2005).

Global warming, though controversial, may play a fundamental role in destabilizing primary productivity in marine food webs (Kirby et al. 2009, Bakun et al. 2010). The possible interaction with environmental fluctuations (salinity, acidification, turbidity, change in currents among others) is still an open question. For instance, when a species becomes overabundant the probability of outbreaks that induce the collapse of functional groups increases significantly (Bakun et al. 2010). Such dynamics have been reported in regime shifts in kelp forests, coral reefs and estuaries (Jackson et al. 2001).

6. Impacts on ecosystems and human well-being

Overfishing has depleted half the world's commercial stocks in the second half of the 20th century (Ecosystem Assessment 2005). Some collapsed stocks have remained at under 10% of their previous sizes even after decades of fishing closure (Ainley and Blight 2009). Depletion of fish stocks has been estimated to have affected the employment of roughly 14 million fishermen, 12 million of which correspond to artisanal fisheries (Hassan et al. 2005). Fish catches are projected to further decrease in the 21st century affecting protein sources for people, especially in poor regions (Hassan et al. 2005). The estimated current contribution of fisheries to human protein consumption is 29 million tons produced industrially and 24 million tons in small-scale fisheries (Hassan et al. 2005).

Overfished marine ecosystems may experience substantial changes in their food webs (Jackson et al. 2001, Crowder et al. 2008). These changes may be exacerbated by destabilization of the frequency in the nutrient inputs. Extreme events associated with climate change may reduce mixing and hence nutrient input, primary production and fishery productivity. Extreme events may also lead to excess nutrient input in cases where upwelling is enhanced, increasing primary production and generating optimal conditions for infestation by zooplanktivore organisms such as jellyfish in cases where their predators have been overfished (Ainley and Blight 2009). The jellyfish then trap nutrients so that less energy flows to higher trophic levels, generating optimal conditions for hypoxia and toxic red tides, symptoms that are increasingly common in coastal marine ecosystems (Bakun et al. 2010). Nektonic organisms (e.g., gelatinous jellyfish in the North Atlantic case, spat in the South Ocean) are well equipped to deal with hash conditions such as increased acidity and decreased dissolved oxygen associated with degraded environments. Such a scenario has been observed in the upwelling system off the Namibian coast (Bakun et al. 2010) and in the North Pacific cod fishery (Kirby et al. 2009). In addition, fishery pressure on filter-feeding fishes like sardine exacerbates the problem by favoring jellyfish outbreaks.

7. Management options for preventing or reversing regime shift

While some scholars suggest that collapsed fisheries are irreversible due to the synergistic effects among anthropogenic climate forcing, fishing pressure and food web mechanisms (Kirby et al. 2009), the Millennium Ecosystem Assessment (Hassan et al. 2005) offer a synthetic set of managerial options for addressing fisheries collapse.

First of all, destructive practices such as bottom trawling must be avoided. Developing alternative technologies and reduction of fishing effort are suggested. Marine protected areas (MPAs) can play an important role, and need to cover ecologically significant areas, including different habitats, ensuring connectivity among them. In the policy arena, comprehensive policies that share responsibilities at the international level are required. The international policy instruments (e.g., FAO's Code of Conduct for Responsible Fisheries, the Convention on the Conservation of Migratory Species of Wild Animals) that already exist need to be further supported. On the national level, policies for management of coastal and oceanic areas need to be integrated (Hassan et al. 2005). In addition, the application of the precautionary principle in policy making appeal for taking the fishing mortality associated with maximum sustainable yield as a limit reference point to be avoided rather than a target that is often exceeded (Hassan et al. 2005).

In fact, some stocks have recovered in the US due to such policy shift, which includes fishing closures and implementation of management measures for bottom fishing. Examples include George Bank haddock, Atlantic scallops, George Bank yellowtail flounder, Atlantic stripped bass, Atlantic Arcadian redfish, Pacific chub mackerel, and Pacific sardine. However, their biomass is still below historic levels, and they constitute the exception rather than the rule when looking the global picture (Hassan et al. 2005).

Second, fishery subsidy policies cannot be further supported. Such subsidies have created market failures inducing the depletion and collapse of several fish stocks. Poverty and unequal welfare distribution issues need to be addressed since most of coastal poor communities rely upon fishing as a primary source of protein. A healthy life and adequate nutrition is a human right, hence, their dependency on natural resources must be addressed through development strategies (education, health, non-fishing-related employment) that reduce pressure on natural resources (Hassan et al. 2005).

In addition, in small closed food webs systems (3 to 4 trophic levels), biomanipulation has been suggested to manage one of the symptoms of degraded marine environments, namely eutrophication. This involves increasing the population of predatory fish such as bass, pike and walleye through stocking or reduced angling quotas. Increased populations of these predators leads to a decrease in the level of zooplanktivores. This in turn allows an increase in the population of planktivores that graze on the algae and zooplanckton, helping to reduce the algal density and phytoplankton respectively (Smith & Schnider 2009).

The role of connectivity in food webs, the effect of environmental variability, as well as social, cultural, economical and political attributes should be taken into account to make better managerial decisions (Crowder et al. 2008).

8. Links to other regime shifts

Simplification of marine food webs, hypoxia, marine eutrophication, climate warming (less NPP, more CO_2 in atmosphere), kelp transitions, coral to algae dominance, vegetation climate interactions.

9. **Key direct drivers of the RS**
    1. Vegetation conversion and habitat fragmentation
    2. Harvest and resource consumption
    3. External inputs (eg fertilizers, pest control, irrigation)
    4. Adoption of new technology (eg new fishing nets)
    5. Infrastructure development (eg roads, pipelines)
    6. Species introduction or removal
    7. Disease
    8. Soil erosion & land degradation
    9. Environmental shocks (eg fire, floods, droughts)
    10. Global climate change

10. **Impacts on ecosystem services**
    - 10.1. Provisioning services
        - Freshwater
        - Food Crops
        - Livestock
        - Fisheries
        - Wild animal and plant foods
        - Timber
        - Woodfuel
        - Other crops (eg cotton)
    - 10.2. Regulating services
        - Air quality regulation
        - Climate regulation
        - Water purification
        - Water regulation
        - Regulation of soil erosion
        - Pest & Disease regulation
        - Pollination
        - Natural hazard regulation
    - 10.3. Cultural services
        - Recreation
        - Aesthetic values
        - Knowledge and educational values
        - Spiritual and religious
    - 10.4. Biodiversity

11. **Impacts on Key Ecosystem Processes**
    - 11.1. Soil formation
    - 11.2. Photosynthesis
    - 11.3. Primary production

11.4. Nutrient cycling
11.5. Water cycling

12. **Impacts on Human Well-being**
    12.1. Food and nutrition
    12.2. Health (eg toxins, disease)
    12.3. Livelihoods and economic activity
    12.4. Security of housing & infrastructure
    12.5. Cultural, aesthetic and recreational values
    12.6. Social conflict
    12.7. No direct impact

13. **Ecosystem type in which the RS occurs**
    13.1. Marine & coastal
    13.2. Freshwater lakes & rivers
    13.3. Temperate & Boreal Forests
    13.4. Tropical Forests
    13.5. Moist savannas & woodlands
    13.6. Drylands & deserts (below ~500mm rainfall/year)
    13.7. Grasslands
    13.8. Tundra
    13.9. Polar
    13.10. Planetary

14. **Land use under which the RS occurs**
    14.1. Urban
    14.2. Small-scale subsistence crop cultivation
    14.3. Large-scale commercial crop cultivation
    14.4. Intensive livestock production (eg feedlots, dairies)
    14.5. Extensive livestock production (natural rangelands)
    14.6. Timber production
    14.7. Fisheries
    14.8. Mining
    14.9. Conservation
    14.10. Tourism
    14.11. Land use impacts are primarily off-site (e.g. dead zones in the ocean caused by fertilizer use in the continental interior; in these cases, also indicate the relevant land uses above)

15. **Typical spatial scale at which RS occurs**
    15.1. Local/landscape (e.g. lake, catchment, community)
    15.2. Sub-continental/regional (e.g. southern Africa, Amazon basin)

(actual RS mechanism occurs at the regional scale OR cumulative impact/extent of local-scale RS is regional in scale)

15.3. Global

16. **Typical time scale over which RS occurs**
    16.1. Weeks
    16.2. Months
    16.3. Years
    16.4. Decades
    16.5. Centuries
    16.6. Unknown

17. **Reversibility of RS**
    17.1. Irreversible (on 100 year time scale)
    17.2. Hysteretic
    17.3. Readily reversible
    17.4. Unknown

18. **Confidence: Existence of RS**
    1. Speculative – Regime shift has been proposed, but little evidence as yet
    2. Contested – Reasonable evidence both for and against the existence of RS
    3. Well established – Wide agreement in the literature that the RS exists

19. **Confidence: Mechanism underlying RS**
    19.1. Speculative – Mechanism has been proposed, but little evidence as yet
    19.2. Contested – Multiple proposed mechanisms, reasonable evidence both for and against different mechanisms
    19.3. Well established – Wide agreement on the underlying mechanism

20. **Evidence**
    1. Models
    2. Paleo-observation
    3. Contemporary observations
    4. Experiments
    5. Other

21. **Contributors**

Juan Carlos Rocha
Stockholm Resilience Centre
juancarlosrochag@gmail.com

Oonsie Biggs
Susa Niiranen

22. Key References

Bibliography

Ainley, D. G. and L. K. Blight. 2009. Ecological repercussions of historical fish extraction from the Southern Ocean. Fish and Fisheries **10**:13-38.

Bakun, A., D. Field, A. Redondo-Rodriguez, and S. Weeks. 2010. Greenhouse gas, upwelling-favorable winds, and the future of coastal ocean upwelling ecosystems. Global Change Biol **16**:1213-1228.

Behrenfeld, M. J., R. T. O'Malley, D. A. Siegel, C. R. Mcclain, J. L. Sarmiento, G. C. Feldman, A. J. Milligan, P. G. Falkowski, R. M. Letelier, and E. S. Boss. 2006. Climate-driven trends in contemporary ocean productivity. Nature **444**:752-755.

Berkes, F. 2006. From community-based resource management to complex systems: The scale issue and marine commons. Ecology and Society **11**:45.

Carpenter, S. K., O. 2003. Regime shifts in lake ecosystems: pattern and variation. Ecology Institute.

Crona, B. 2006. Supporting and enhancing development of heterogeneous ecological knowledge among resource users in a Kenyan seascape. Ecology and Society **11**.

Crowder, L. B., E. L. Hazen, N. Avissar, R. Bjorkland, C. Latanich, and M. B. Ogburn. 2008. The Impacts of Fisheries on Marine Ecosystems and the Transition to Ecosystem-Based Management. Annu Rev Ecol Evol S **39**:259-278.

Ecosystem Assessment, M. 2005. Ecosystems and human well-being: synthesis.137.

Hassan, R. M., R. Scholes, and N. Ash. 2005. Ecosystems and human well-being: current state and trends.

Hilborn, R. 2007. Reinterpreting the State of Fisheries and their Management. Ecosystems **10**:1362-1369.

Jackson, J. 2008. Ecological extinction and evolution in the brave new ocean. Proceedings of the National Academy of Sciences of the United States of America **105**:11458-11465.

Jackson, J., M. Kirby, W. Berger, K. Bjorndal, L. Botsford, B. Bourque, R. Bradbury, R. Cooke, J. Erlandson, J. Estes, T. Hughes, S. Kidwell, C. Lange, H. Lenihan, J. Pandolfi, C. Peterson, R. Steneck, M. Tegner, and R. Warner. 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science **293**:629-638.

Kirby, R. R., G. Beaugrand, and J. A. Lindley. 2009. Synergistic Effects of Climate and Fishing in a Marine Ecosystem. Ecosystems **12**:548-561.

Litzow, M. A. and D. Urban. 2009. Fishing through (and up) Alaskan food webs. Canadian Journal of Fisheries and Aquatic Sciences **66**:201-211.

Mollmann, C., R. Diekmann, B. Muller-Karulis, G. Kornilovs, M. Plikshs, and P. Axe. 2009. Reorganization of a large marine ecosystem due to atmospheric and anthropogenic pressure: a discontinuous regime shift in the Central Baltic Sea. Global Change Biology **15**:1377-1393.

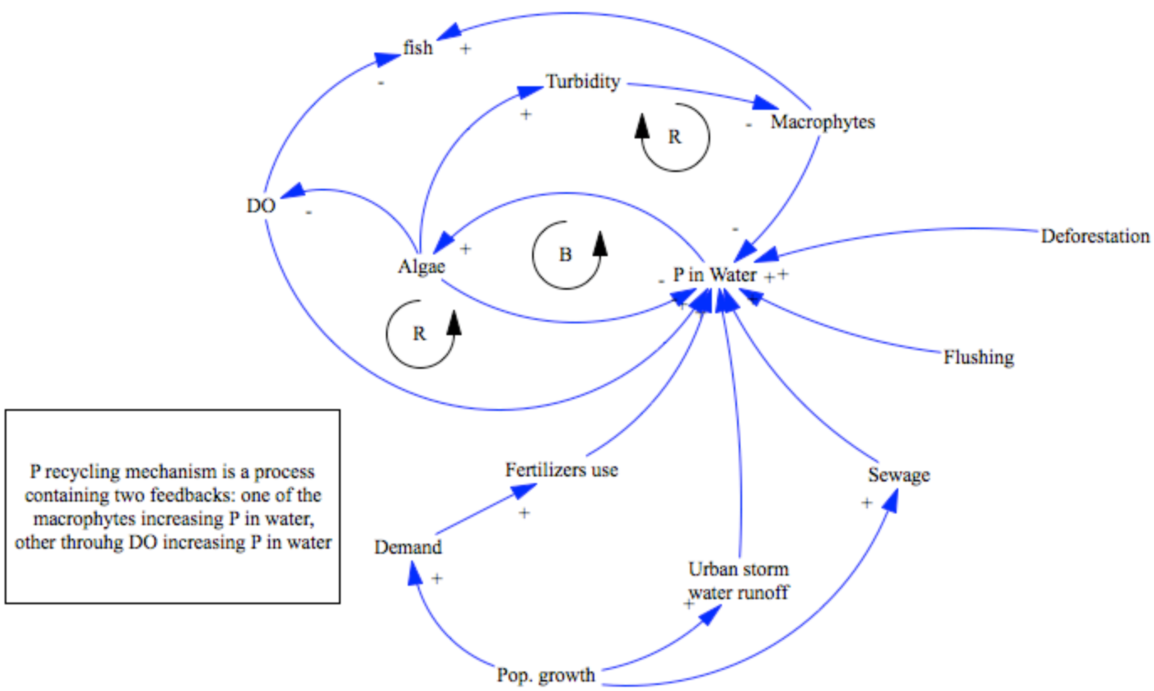
Moxnes, E. 2005. Policy sensitivity analysis: simple versus complex fishery models. System Dynamics Review.

Ostrom, E. 1990. Governing the commons : the evolution of institutions for collective action.

Pauly, D., V. Christensen, J. Dalsgaard, R. Froese, and F. Torres. 1998. Fishing down marine food webs. Science **279**:860-863.
Scheffer, M. 2009. Critical transitions in nature and society.
Scheffer, M., E. H. Nes, M. Holmgren, and T. Hughes. 2008. Pulse-Driven Loss of Top-Down Control: The Critical-Rate Hypothesis. Ecosystems **11**:226-237.
Smith, Val H; and Schindler, David W. 2009. Eutrophication science: where do we go from here?
Trends in Ecology & Evolution 24 (4) pp. 201-207

FRESHWATER EUTROPHICATION
by Juan Carlos Rocha
juancarlosrochag@gmail.com

2. Diagram



3. Summary

Freshwater eutrophication refers to the build-up of nutrients in freshwater ecosystems such as lakes, reservoirs and rivers, leading to excessive plant growth or algal blooms. The main driver of freshwater eutrophication is nutrient pollution in the form of phosphorous from agricultural fertilizers, sewage effluent and urban stormwater runoff. Beyond a certain threshold of phosphorous accumulation, a recycling mechanism is activated which can keep the system locked in a eutrophic state even when nutrient inputs are substantially reduced. Fisheries and aesthetic values are among the ecosystem services affected by freshwater eutrophication.

4. Description of the regime shift dynamics

Many freshwater ecosystems exhibit two different ecological regimes or configurations, each stabilized by a distinct set of feedbacks. In one regime, phosphorous inputs, phytoplankton biomass (algae), and phosphorous recycling from lake or river sediments are typically low, and the water is clear. Such systems are called oligotrophic. In the other regime, phosphorous inputs, phytoplankton biomass, and phosphorous recycling from sediments are usually high, and the water is turbid or murky. Such systems are called eutrophic (Smith 1998, Carpenter 2003, Smith & Schindler 2009).

The shift from oligotrophic to eutrophic conditions occurs when a body of water – a lake, river or reservoir – accumulates excessive nutrients. This process can happen naturally over several centuries as a lake ages and accumulates sediments and nutrients from the surrounding landscape. Nowadays, however, human activities cause freshwater eutrophication to occur much more rapidly and extensively than in the past. Because freshwater ecosystems are usually phosphorous limited, freshwater eutrophication is typically related to over-enrichment by phosphorous rather than other nutrients. Excess phosphorous inputs to freshwater systems typically derive from fertilizers applied to agricultural lands, urban storm water runoff, and untreated sewage disposal (Carpenter 2003). Deforestation and poor agricultural management can accelerate, in magnitude and frequency, the runoff of phosphorous from agricultural lands (Smith & Schindler 2009).

The accumulation of phosphorous in the water column usually triggers excessive production of phytoplankton (i.e., algal blooms). In faster-flowing rivers, phytoplankton tends to be washed downstream, and excessive growth of plants such as water hyacinth (*Eichhornia*), duckweed (*Lemna*) or water fern (*Azolla*) may be stimulated instead (Scheffer 1997).

Algal blooms, in turn, trigger larger ecosystem changes. The excessive rates of plant growth and decay that characterize algal blooms lead to depletion of oxygen levels in the water. When oxygen levels fall below the levels needed for respiration, it may lead to widespread kills of fish and shellfish. In addition, algal blooms prevent sunlight from penetrating to rooted plants (macrophytes) growing on the bottom of lakes or rivers. Under oligotrophic conditions, these plants help absorb excess phosphorous from the water column and also stabilize the sediments on the lake floor. Shading by excessive algal growth means that rooted plants are unable to photosynthesize adequately and die. Fish and invertebrate species that depend on these macrophytes for food or habitat are then also affected (Carpenter 2003).

Even if nutrient input levels are subsequently decreased, the system may remain locked in a eutrophic state. The feedback that keeps the system eutrophic is the activation of a phosphorous recycling mechanism. In shallow lakes and rivers, the sediments on the lake or river floor typically contain high levels of phosphorous that have accumulated from the settling out of decomposing algae and other organisms. Under eutrophic conditions, the loss of the rooted plants means that the sediments can easily become resuspended due to wave action or the activities of bottom-feeding fish. The resuspended nutrients then become reavailable, promoting further growth of algae, and thereby reinforcing the eutrophic state (Scheffer 1997; Scheffer *et al*. 1993).

In deep lakes, the eutrophic state is maintained by a different mechanism. In deep lakes temperature gradients create different layers of water: the epilimnion or upper layer is warm and well oxygenated, while the hypolimnion is a lower and colder water layer (Carpenter 2003). When the hypolimnion is oxygenated, phosphorous is captured by iron molecules in an insoluble form. Thus, it is not available to primary producers such as algae. However, algal blooms lead to the depletion of oxygen levels in the lower water layers through the decay of organic matter. When oxygen levels become depleted, phosphate is released in a soluble form that can be used by algae. Algal blooms thereby trigger the recycling of phosphorous in a way that reinforces the eutrophic state (Carpenter 2003).

The degree of reversibility from eutrophic to oligotrophic conditions varies greatly. In some lakes oligotrophic conditions have been restored rapidly after reduction of phosphorous inputs, while in other cases lakes have remained eutrophic despite prolonged reductions in phosphorous inputs and even dredging of the lake sediments (Carpenter 2003; Carpenter et al. 1999). Even though the consequences of global warming are not well understood, it will either exacerbate or mitigate eutrophication.

5. Impact on ecosystems, ecosystem services and human well-being

Eutrophication induces large changes in ecological communities and hence in the configuration of food webs. Primary producers (algae) experience massive population increases, while heterotrophic fish and shellfish may experience large population declines due to lack of oxygen. Consequently less energy is captured by higher trophic levels. Rooted macrophytes tend to be lost due to shading by algae. The loss of macrophytes has cascading effects on zooplankton and other organisms that depend on these plants for habitat and food (Carpenter 2003).

These food web changes are accompanied by changes in the phosphorous and carbon cycles of the affected ecosystems: larger quantities of phosphorous and carbon are cycled through the ecosystem at higher rates. In addition, large swings in the amount of dissolved oxygen in the water may take place (Carpenter 2003).

Changes in the ecological communities resulting from eutrophication can make a system more vulnerable to invasion by new species or to disease outbreaks. Nutrient-rich waters are a perfect environment for the development of pathogens like cholera (Smith & Schindler 2009). Some algal blooms produce toxic compounds that can move up the food chain resulting in illness or death when consumed by animals or humans (Lawton & Codd 1991).

Eutrophication has several direct consequences for human well-being (Postel & Carpenter 1997, Carpenter *et al.* 1998):

- Loss of fish species from eutrophic ecosystems impact commercial, subsistence, and recreational fishing;
- Recreational use of water bodies for swimming, boating and angling are reduced,
- The value of lakeside properties and recreational areas are reduced due to unpleasant odours and murky water,
- The costs of water treatment for domestic, industrial and agricultural uses increases,

- Toxins produced by certain algal blooms may cause death of livestock (and humans) if eutrophic water is used for drinking,
- Biotoxins produced by algae may be taken up by shellfish such as mussels and oysters, and can lead to the poisoning of humans when consumed (Lawton & Codd 1991).

6. Management options for preventing and reversing the regime shift

Freshwater ecosystems react in different ways to increases and reductions in nutrient loading, depending on their hydrogeomorphological features, water current patterns, and biological characteristics. Different strategies for managing eutrophication will therefore be required in different settings (Smith 2003).

The main management option, both for prevention and restoration, is to reduce phosphorous inputs. Developing technology and economic incentives to close the nutrient cycle at the local (farm) level is crucial. Reforestation of watersheds can help buffer the impact of rainstorms on soil erosion and phosphorous runoff. Importantly, phosphorous sources tend to be concentrated spatially in the landscape. Reducing runoff from a small number of high source areas can have a major impact on water quality, and should be a priority.

If the ecosystem is hysteretic, more active intervention may be needed to reverse eutrophic conditions. For instance, lake floor sediments can be dredged, or phosphorus can be immobilized by adding aluminium sulphate (Carpenter 2003). Bottom-feeding fish such as carp, which physically stir up lake-floor sediments when feeding, can also be removed.

Another option for managing eutrophication is through "biomanipulation" of food webs. This involves increasing the population of predatory fish such as bass, pike and walleye through stocking or reduced angling quotas. Increased populations of these predators leads to a decrease in the level of zooplanktivores. This in turn allows an increase in the population of planktivores that graze on the algae, helping to reduce the algal density. Results from biomanipulation studies have given rise to the idea that, to reduce eutrophication, lakes should be managed to contain an even, rather than odd, number of trophic levels (Smith & Schnider 2009).

7. Related regime shifts

Hypoxia, fisheries collapse, marine and coastal eutrophication

8. Key direct drivers of the RS

8.1. Habitat conversion or fragmentation
8.2. Harvest and resource consumption
8.3. External inputs (eg fertilizers, pest control, irrigation)
8.4. Adoption of new technology (eg new fishing nets)
8.5. Infrastructure development (eg roads, pipelines)
8.6. Species introduction or removal
8.7. Disease
8.8. Soil erosion & land degradation

8.9. Environmental shocks (eg fire, floods, droughts)
8.10. Global climate change

9. Impacts on ecosystem services

- 9.1. Provisioning services:
  - 9.1.1. Freshwater
  - 9.1.2. Food Crops
  - 9.1.3. Livestock
  - 9.1.4. Fisheries
  - 9.1.5. Wild animal and plant foods
  - 9.1.6. Timber
  - 9.1.7. Woodfuel
  - 9.1.8. Other crops (eg cotton)
- 9.2. Regulating services
  - 9.2.1. Air quality regulation
  - 9.2.2. Climate regulation
  - 9.2.3. Water purification
  - 9.2.4. Water regulation
  - 9.2.5. Regulation of soil erosion
  - 9.2.6. Pest & Disease regulation
  - 9.2.7. Pollination
  - 9.2.8. Natural hazard regulation
- 9.3. Cultural services
  - 9.3.1. Recreation
  - 9.3.2. Aesthetic values
  - 9.3.3. Knowledge and educational values
  - 9.3.4. Spiritual and religious
- 9.4. Biodiversity

10. Impacts on Key Ecosystem Processes

- 10.1. Soil formation
- 10.2. Photosynthesis
- 10.3. Primary production
- 10.4. Nutrient cycling
- 10.5. Water cycling

11. Impacts on Human Well-being

- 11.1. Food and nutrition
- 11.2. Health (eg toxins, disease)
- 11.3. Livelihoods and economic activity
- 11.4. Security of housing & infrastructure
- 11.5. Cultural, aesthetic and recreational values
- 11.6. Social conflict

11.7. No direct impact

12. Ecosystem type in which the RS occurs

12.1. Marine & coastal
12.2. Freshwater lakes & rivers
12.3. Temperate & Boreal Forests
12.4. Tropical Forests
12.5. Moist savannas & woodlands
12.6. Drylands & deserts (below ~500mm rainfall/year)
12.7. Grasslands
12.8. Tundra
12.9. Polar
12.10. Planetary

13. Land use under which the RS occurs or with which it is associated

13.1. Urban
13.2. Small-scale subsistence crop cultivation
13.3. Large-scale commercial crop cultivation
13.4. Intensive livestock production (eg feedlots, dairies)
13.5. Extensive livestock production (natural rangelands)
13.6. Timber production
13.7. Fisheries
13.8. Mining
13.9. Conservation
13.10. Tourism
13.11. Land use impacts are primarily off-site (e.g. dead zones in the ocean caused by fertilizer use in the continental interior; in these cases, also indicate the relevant land uses above)

14. Typical spatial scale at which RS occurs

14.1. Local/landscape (e.g. lake, catchment, community)
14.2. Sub-continental/regional (e.g. southern Africa, Amazon basin) (actual RS mechanism occurs at the regional scale OR cumulative impact/extent of local-scale RS is regional in scale)
14.3. Global

15. Typical time scale over which RS occurs

15.1. Weeks
15.2. Months
15.3. Years
15.4. Decades
15.5. Centuries
15.6. Unknown

16. Reversibility of RS

16.1. Irreversible (100 year timescale)
16.2. Hysteretic
16.3. Readily reversible
16.4. Unknown

17. Confidence: Existence of RS (IPCC language)

17.1. Speculative – Regime shift has been proposed, but little evidence as yet
17.2. Contested – Reasonable evidence both for and against the existence of RS
17.3. Well established – Wide agreement in the literature that the RS exists

18. Confidence: Mechanism underlying RS (IPCC language)

18.1. Speculative – Mechanism has been proposed, but little evidence as yet
18.2. Contested – Multiple proposed mechanisms, reasonable evidence both for and against different mechanisms
18.3. Well established – Wide agreement on the underlying mechanism

19. Evidence

19.1. Models
19.2. Paleo-observation
19.3. Contemporary observations
19.4. Experiments
19.5. Other

20. Contributors and Reviewer

Juan Carlos Rocha
Intern at Stockholm Resilience Centre and Beijer Institute
juancarlosrochag@gmail.com

Reinette (Oonsie) Biggs
Researcher at Stockholm Resilience Centre
oonsie.biggs@stockholmresilience.su.se

21. **Last updated**: July 24, 2009

22. Key References

Carpenter, Stephen. 2003. Regime shifts in lake ecosystems: patterns and variation. International Ecology Institute. 199p

Carpenter, S; Ludwig, D; W. Brock. 1999. Management of eutrophication for lakes subject to potentially irreversible change. Ecological Applications 9 (3) pp. 751-771

Carpenter, S. R., Bolgrien, D., Lathrop, R. C., Stow, C. A., Reed, T. and Wilson, M. A. (1998). Ecological and economic analysis of lake eutrophication by nonpoint pollution. *Australian Journal of Ecology* **23,** 68-79.

Lawton, L. A. and Codd, G. A. (1991). Cyanobacterial (blue-green algae) toxins and their significance in UK and European waters. *Journal of Soil and Water Conservation* **40,** 87-97.

Postel, S. L. and Carpenter, S. R. (1997). Freshwater ecosystem services. In: *Nature's Services* (Daily, G. C. ed.), pp. 195-214. Washington DC, USA:

Scheffer, M. (1997). *The ecology of shallow lakes*. London: Chapman and Hall.

Scheffer, M., Hosper, S. H., Meijer, M.-L., Moss, B. and Jeppesen, E. (1993). Alternative equilibria in shallow lakes. *Trends in Ecology and Evolution* **8,** 275-279.

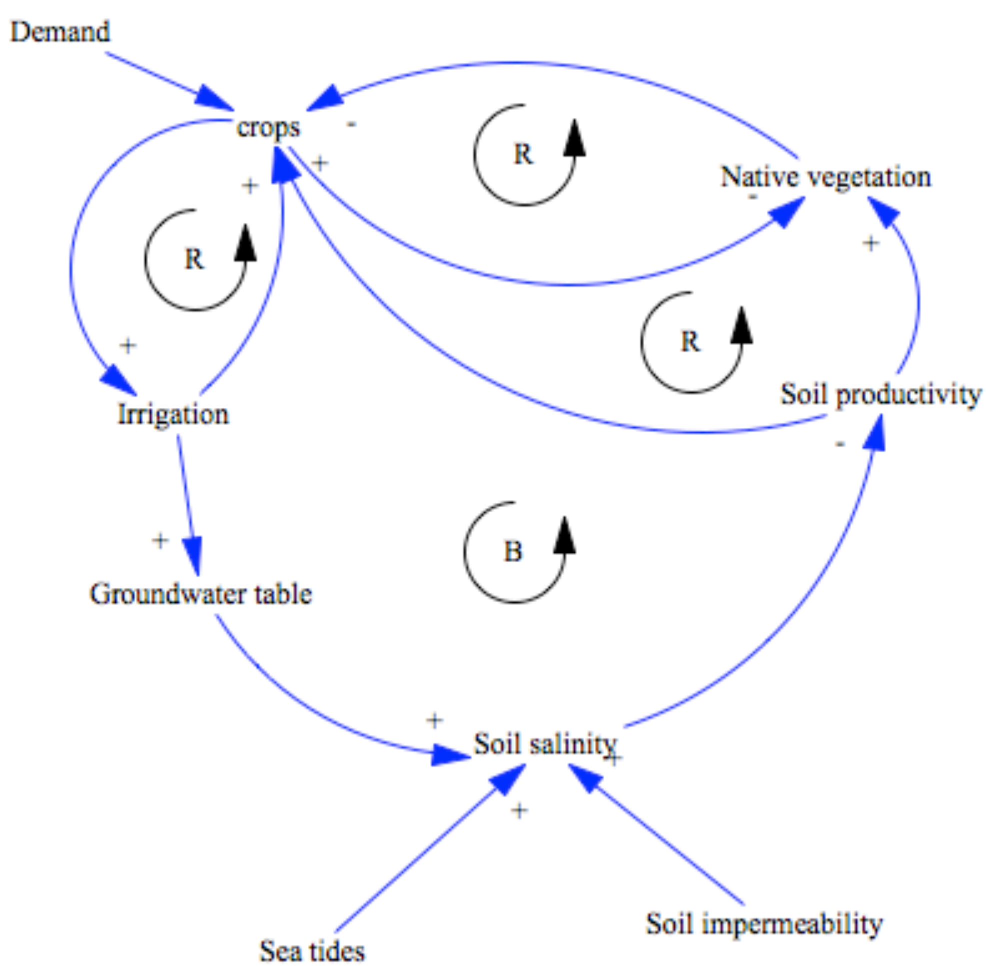
Smith, V. H. (1998). Cultural eutrophication of inland, estuarine and coastal waters. In: *Successes, limitations and frontiers in ecosystem science* (Pace, M. L. and Groffman, P. M. ed.), pp.7-49. New York, USA: Springer-Verlag.

Smith, Val H; and Schindler, David W. 2009. Eutrophication science: where do we go from here? Trends in Ecology & Evolution 24 (4) pp. 201-207.

Smith, V. H. (2003). Eutrophication of freshwater and coastal marine ecosystems. *Environmental Science and Pollution Research* **10,** 126-139.

1. # Soil salinization

2. *Diagram of regime shift dynamics*



3. *Summary of the regime shift*

Soil salinization refers to an excessive accumulation of salt in the topsoil and typically occurs in irrigated arid and semi-arid areas. Salinization is usually associated with elevated water tables. Salts that have accumulated in the deep soil layers are moved upwards by the rising water table. Once the water table is near the surface (c. 2m, depending on soil type) evapotranspiration draws the salt upwards from the water table into the topsoil through capillary transport. Salinization may also result directly from irrigation with salty water.

Elevated water tables typically result from the clearing of perennial deep-rooted native vegetation, and its replacement by seasonal, shallow-rooted agricultural crops that have a lower ability to absorb and transpire water. This causes the hydrological balance to be disturbed and has considerable consequences. Soil salinization leads to poor crop growth, dramatically reducing the productivity of agricultural land. It may also affect the landscape surrounding agricultural fields with impacts on biodiversity, aesthetic and recreational values.

4. *Detailed description of regime shift dynamics*

Soil salinization, an excess accumulation of salt in the root-zone of the soil profile, can occur for a variety of reasons. Saline seeps may appear when infiltration of water is blocked by an impermeable layer in the soil, when sea tidal waves deposit salt, or when saline groundwater is used for irrigation. However, the most extensive and serious salinity problems derive from agricultural activity in arid and semi-arid areas (Abrol et al, 1988).

The first step in the salinization process is typically a shift from native vegetation to crops and pastures. Native vegetation in semi-arid areas is usually perennial and deep-rooted, because it is adapted to survive drought periods. These features enable the vegetation to fully exploit the annual input of rainwater, so that little or no water penetrates to the groundwater table except in exceptionally wet years. The water table is therefore kept well below the root-zone, the most important layer of soil for plant growth (Anderies, 2005, Anderies et al, 2006, Walker & Salt, 2006).

The shift to crops and pastures alters the structure of the system by introducing seasonal shallow-rooted vegetation which is usually unable to cope with seasonal dry spells and therefore requires irrigation. The amount of water artificially added to the system changes the hydrological equilibrium that existed before the conversion to agriculture (Abrol et al, 1988). The increased infiltration of water results in a rising groundwater table which, once it reaches the root-zone, impedes crop growth and reduces the productivity of the land (Abrol et al, 1988).

Groundwater usually contains suspended and dissolved salts that have accumulated in the lower soil layers through past leaching. When the rising water table reaches about 2 meters from the soil surface, these salts are transported to the surface by capillary action. This increases the salt concentration in the topsoil to an extent which adversely affects the growth of most crop plants (Lazof & Bernstein, 1999). High concentrations of salt in the topsoil reduces the uptake of water by plants and impedes the absorption of nutrients. Some salts may also be toxic to plants when present in high concentrations.

During salinization, the system therefore shifts from a state characterized by a deep watertable that is maintained by deep-rooted vegetation, to a state characterized by a shallow watertable, shallow-rooted vegetation, and a high density of salt in the root-zone. The lack of deep-rooted vegetation, the need for irrigation, and the demand for intensive crop production creates a reinforcing mechanism which may lock the system into this undesirable stable.

5. *Impacts on ecosystems and human well-being*

Soil salinization has dramatic effects on the structure and the functioning of the social-ecological system. The physical and chemical characteristics of the soil shift to a state where the topsoil is saturated with soluble salts and its pH value approaches neutral (Abrol et al, 1988). The primary effects of saline soils are to reduce the amount of water available to plants, impede the uptake of nutrients (Lazof et al., 1999) and block the germination of seeds (Abrol et al, 1988). Sodium also disperses clay particles, which destroys soil structure and makes the soil much less permeable to water. These changes result in poor and spotty stands of crops, uneven and stunted growth and poor yields (Abrol et al, 1988). Only a few very salt-tolerant crops, which are usually less desirable, grow satisfactorily under saline conditions.

The losses in agricultural productivity associated with soil salinization directly impacts human well-being. Reduced agricultural production undermines economic activities that are vital for farmers' livelihoods. In addition, the excessive accumulation of salt in the soil can also damage roads and rails and corrode pipes and cables (George et al., 2005).

Soil salinization may further affect the areas surrounding agricultural fields, contributing to the loss of both plant and animal biodiversity in the catchment (Wall et al., 1999). Food-webs become simplified and, because of the lack of functional redundancy, are more vulnerable to external disturbances (Wall et al., 1999). The aesthetic and recreational values of native vegetation are reduced to what a partially barren landscape, potentially with visible salt crusts, may offer.

Management options for preventing and reversing the regime shift

Once a catchment has been converted from native vegetation to crops or pastures two critical variables control the rise of the water table. First, the number of deep-rooted plants and, second, the degree of irrigation. Thus, prevention of soil salinization includes maintaining a mix of deep-rooted perennial vegetation and crops in order to prevent the rise of the water table, and managing the amount of irrigation water that is applied (Walker & Salt, 2006).

Once the root-zone has become saline, there are several short-term management options to "reclaim the saline soil" (i.e. remove the accumulated salt). These include mechanically scraping surface salt (which leads to the problem of salt disposal), or flushing the topsoil using water (which has poor efficacy and might exacerbate the problem in situations with high water tables) (Abrol et al, 1988). A more efficient option is to create a surface water drainage system using field ditches to avoid the deposition of salt, combined with subsurface water pumping to decrease the water table level (Anderies et al, 2006, Walker & Salt, 2006). The expenses arising from the implementation and maintenance of such drainage systems are, however, substantial (Abrol et al, 1988).

Long-term methods to keep the groundwater level below the root-zone include planting of deep-rooted vegetation (Walker & Salt, 2006) and salt tolerant plants (Abrol et al, 1988). Apart from the direct effects of lowering the water table and reducing the salt concentration in the top soil, this strategy can contribute to increasing the diversity of the agricultural system. This may improve soil health (Abrol et al, 1988) and make the ecosystem less vulnerable to disturbances (Walker & Salt, 2006).

The social system also offers great potential for managing soil salinity. Water pricing systems, long-term tenancy of the land, use of appropriate technology and farmer's education can contribute significantly towards the goal of maintaining productive land (Abrol et al, 1988).

6. *Links to other regime shifts*
   Currently unknown.

7. *Key direct drivers of the RS*
   7.1. Vegetation conversion and habitat fragmentation
   7.2. Harvest and resource consumption
   7.3. External inputs (eg fertilizers, pest control, irrigation)
   7.4. Adoption of new technology (eg new fishing nets)
   7.5. Infrastructure development (eg roads, pipelines)
   7.6. Species introduction or removal
   7.7. Disease
   7.8. Soil erosion & land degradation
   7.9. Environmental shocks (eg fire, floods, droughts)
   7.10. Global climate change

8. *Impacts on ecosystem services*
   8.1. Provisioning services:
      8.1.1. Freshwater
      8.1.2. Food Crops
      8.1.3. Livestock
      8.1.4. Fisheries
      8.1.5. Wild animal and plant foods

        8.1.6. Timber
        8.1.7. Woodfuel
        8.1.8. Other crops (eg cotton)
    8.2. Regulating services
        8.2.1. Air quality regulation
        8.2.2. Climate regulation
        8.2.3. Water purification
        8.2.4. Water regulation
        8.2.5. Regulation of soil erosion
        8.2.6. Pest & Disease regulation
        8.2.7. Pollination
        8.2.8. Natural hazard regulation
    8.3. Cultural services
        8.3.1. Recreation
        8.3.2. Aesthetic values
        8.3.3. Knowledge and educational values
        8.3.4. Spiritual and religious
    8.4. Biodiversity

9. *Impacts on Key Ecosystem Processes*
    9.1. Soil formation
    9.2. Photosynthesis
    9.3. Primary production
    9.4. Nutrient cycling
    9.5. Water cycling

10. *Impacts on Human Well-being*
    10.1. Food and nutrition
    10.2. Health (eg toxins, disease)
    10.3. Livelihoods and economic activity
    10.4. Security of housing & infrastructure
    10.5. Cultural, aesthetic and recreational values
    10.6. Social conflict
    10.7. No direct impact

11. *Ecosystem type in which the RS occurs*
    11.1. Marine & coastal
    11.2. Freshwater lakes & rivers
    11.3. Temperate and boreal forests
    11.4. Tropical Forests
    11.5. Moist savannas and woodlands
    11.6. Drylands and deserts (below ~500mm per year)
    11.7. Grasslands

11.8. Tundra
11.9. Polar
11.10. Planetary

12. Land use under which the RS occurs

12.1. Urban
12.2. Small-scale subsistence crop cultivation
12.3. Large-scale commercial crop cultivation
12.4. Intensive livestock production (eg feedlots, dairies)
12.5. Extensive livestock production (natural rangelands)
12.6. Timber production
12.7. Fisheries
12.8. Mining
12.9. Conservation
12.10. Tourism
12.11. Land-use impacts are primarily offsite (eg deadzones in the ocean; in these cases also indicate the relevant land uses above)

13. Typical spatial scale at which RS occurs

13.1. Local/landscape (e.g. lake, catchment, community)
13.2. Sub-continental/regional (e.g. southern Africa, Amazon basin)
13.3. Global

14. Typical time scale over which RS occurs

14.1. Weeks
14.2. Months
14.3. Years
14.4. Decades
14.5. Centuries
14.6. Unknown

15. Reversibility of RS

15.1. Irreversible (on 100 year time scale)
15.2. Hysteretic
15.3. Readily reversible
15.4. Unknown

16. Confidence: Existence of the Regime Shift (IPCC language)

16.1. Speculative – Regime shift has been proposed, but little evidence as yet
16.2. Contested – Reasonable evidence both for and against the existence of regime shift
16.3. Well established – Wide agreement in the literature that the RS exists

17. Confidence: Mechanism underlying the Regime Shift (IPCC language)

17.1. Speculative – Mechanism has been proposed, but little evidence as yet
17.2. Contested – Multiple proposed mechanisms, reasonable evidence both for and against different mechanisms
17.3. Well established – Wide agreement on the underlying mechanism

18. Evidence

18.1. Models
18.2. Paleo-observation
18.3. Contemporary observations
18.4. Experiments
18.5. Other

19. Contributors and Reviewers

Matteo Giusti, Master student in Ecosystems Governance and Globalisation
Intern at the Stockholm Resilience Center
matteo.giusti@gmail.com

Reinette Biggs, Stockholm Resilience Centre

20. Last updated

24 August 2009

21. References

Anderies, J. M. (2005). Minimal models and agroecological policy at the regional scale: An application to salinity problems in southeastern Australia. *Regional Environmental Change* **5,** 1-17.

Anderies, J. M., Ryan, P. and Walker, B. H. (2006). Loss of resilience, crisis and institutional change: lessons from an intensive agricultural system in southeastern Australia. *Ecosystems* **9,** 865-878.

Walker, B.H. and D. Salt. 2006. *Resilience Thinking*, Island Press, London.
ISBN 1597260932.

I.P. Abrol, J.S.P. Yadav , F.I. Massoud "Salt-Affected Soils and their Management", Rome, 1988, FAO SOILS BULLETIN 39 , FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, M-53
ISBN 92-5-102686-6

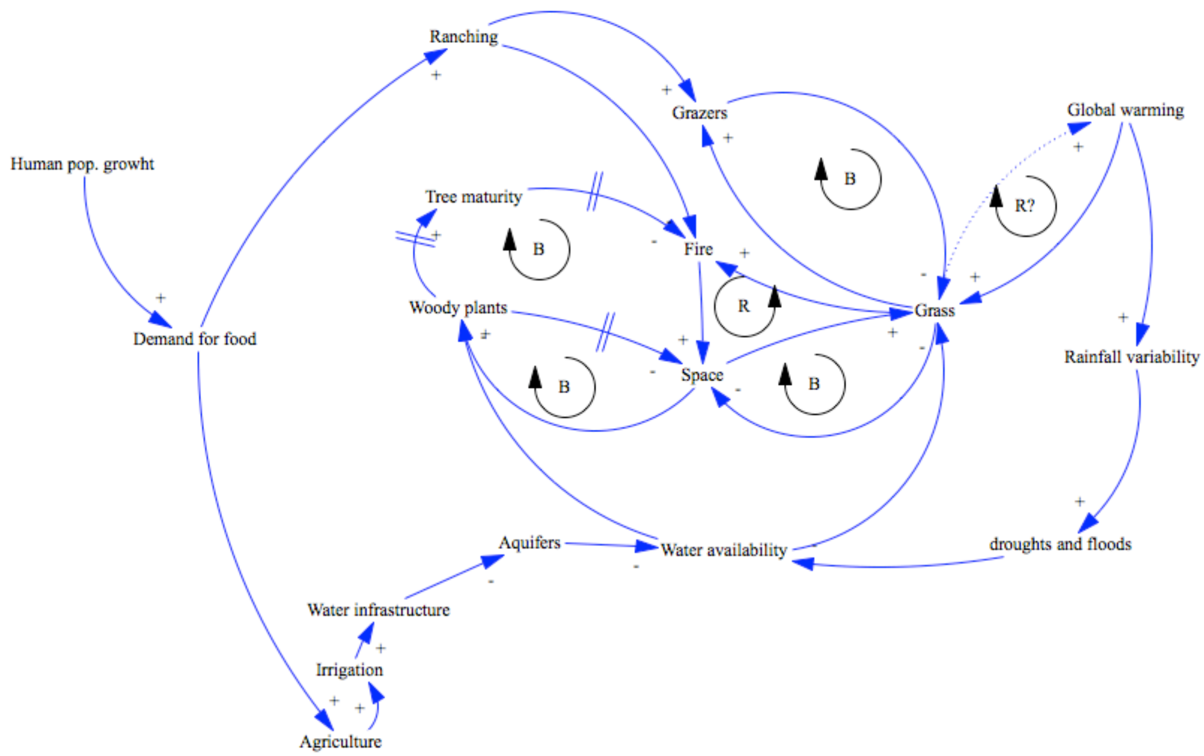
Diana H. Wall, Ross A. Virginia “Controls on soil biodiversity: insights from extreme environments”, Applied Soil Ecology 13 (1999) 137-150

DENNIS B. LAZOF and NIRIT BERNSTEIN, “Effects of salinization on nutrient transport to lettuce leaves : consideration of leaf developmental stage”, New Phytol. (1999), 144, 85±94

Richard George, Ross Kingwell, Janette Hill-Tonkin and Bob Nulsen, “Salinity Investment Framework: Agricultural land and infrastructure”, 2005, Resource Management Technical Report 270

ENCROACHMENT: Grassy to woody savannas.

2. Diagram of regime shift dynamics



3. Summary of regime shift

Woody encroachment occurs when a grassy landscape with a relatively low cover of woody plants rapidly and apparently irreversibly increases in tree or shrub cover. Encroachment typically occurs when savanna landscapes formerly under wild herbivores or nomadic pastoralism are converted to commercial cattle ranching, involving fencing, water provision for livestock, a fixed (sometimes high) stocking rate, and intentional or unintentional grass fire suppression. Encroachment reduces the grass productivity and can make access by cattle difficult, with substantial negative economic impacts on ranchers. Woody encroachment is usually very difficult and costly to reverse. Managerial recommendations therefore focus on avoidance through moderate grazing and fires of sufficient intensity and frequency to prevent the recruitment of young trees.

4. Description of the alternate regimes and reinforcing feedbacks

Savannas are systems that consist of a mixture of woody vegetation (trees or shrubs) and grasses. At small scales (up to about 10 km^2) savanna systems, especially those used for extensive cattle ranching, may stabilize in two different self-reinforcing regimes (Scheffer et al 2001, Walker 1993, Scholes 2003):

Open, grassy savanna regime: In this regime the landscape has a productive grass layer with few mature trees. Trees are unable to establish because the seedlings, while often numerous, are constantly knocked back to ground level by herbivory and fire. There is enough grass after grazing to support a fire with flame-length taller than the young saplings sufficiently often to keep them in a 'fire trap' (Higgins et al. 2000, Roques *et al.*, 2001; Dublin et al. 1990).

Closed, woody savanna regime: In this regime the landscape is dominated by woody shrubs or trees. Once established, woody vegetation is stable because adult trees are seldom killed by herbivory or fire. Completion from the woody plants for water, nutrients and light disproportionately suppresses grass production. As a result, if grazing pressure remains high, there is not enough fuel left to carry fires sufficiently intense and frequent to keep the seedlings from escaping above the flame zone. Established trees may also trap and retain nutrients, and create microclimates that further improve the conditions for tree establishment and growth. The encroachment typically occurs in episodes rather than continuously, and involves a particular set of encroaching species rather than the entire woody community. The long-term outcome (century-scale) is largely unknown, as are the dynamics of reversion to the grassy state.

These alternate regimes can occur at a range of spatial scales. Sometimes larger areas (e.g. an entire cattle ranch) may shift from a grass-dominated to a persistent woody-dominated state (Walker 1993, Dublin et al. 1990). In other cases, the alternate regimes are expressed as a mosaic of small patches of trees or bush interspersed with patches of grass, where the respective patches are highly persistent over time (Rietkerk et al. 2004).

5. Drivers of the regime shift

Bush encroachment refers to a shift from a grassy system to a persistently woody system. Bush encroachment typically occurs in areas used for commercial (as opposed to subsistence, communal, or nomadic) cattle ranching and may follow episodes of sustained severe overgrazing, though not necessarily so. It may also occur under other land uses (Wiegand et al 2006). Bush encroachment involves a change in the outcome of the competitive interaction between woody vegetation (shrubs and trees) and herbaceous vegetation (grasses and herbs), mediated by nutrients, grazing, fire, rainfall variability and use of the either the woody or grassy components by humans (Wiegand *et al.* 2006; Janssen *et al.* 2004, Anderies *et al.,* 2002).

There are several different hypotheses regarding the mechanism by which bush encroachment occurs. Different mechanisms (or combinations of mechanisms) may be important in different places. One proposed mechanism is based on changes in fire regime: in the sustained presence of high numbers of grazers (typically cattle) accumulation of grass fuel is reduced, leading to period without intense fire long enough for woody plants to grow beyond the fire-susceptible stage, which in turn suppresses grass production and fires, further enhancing the establishment of woody vegetation (Higgins et al. 2000, Staver et al. 2009). A related hypothesis notes the elimination of browsers (especially very large browsers such as elephant and giraffe, but also the more-numerous small browsers) from the system when cattle are introduced (Dublin et al. 1990). Another hypothesis focuses on changes in water availability based on the rooting depths of plants: grasses are thought to be more shallowly-rooted than trees, so if grass cover is reduced by overgrazing, more water available for trees, which promotes their growth and establishment, further suppressing grass growth (Noy-Meir 1982). Refinements of these hypotheses emphasize combinations of events, such as a multiyear drought or fireless period providing a "window" for the establishment of trees (Wiegand et al 2006).

Yet other hypotheses focus on the role that increases in global CO_2 levels may play in the observed proliferation of woody plants in many, widely-separated areas of the world during the 20^{th} century. The underlying mechanism is still debated, but several possibilities have been proposed: i) that rising CO_2 levels favour C3 (woody plant) photosynthesis relative to C4 (tropical grass) photosynthesis ii) elevated CO_2 may reduce transpiration of grasses, leading to greater water percolation and therefore favoring deeper rooted woody species, iii) faster growth of woody plants due to CO_2 enrichment, and therefore faster escape of seedlings from susceptibility to fire, iv) investments in carbon-based defense compounds such as tannins, which are the main defense compounds in many encroaching trees but not in grasses (Midgley and Bond 2001, Wiegand et al 2006). Finally, alien species, such as *Prosopis* in South Africa or *Acacia nilotica* in Australia, both deliberately introduced, can play an important role in bush encroachment (Poynton 1990).

It is striking that encroachment is almost unheard of on communal land, and is not universal on commercial farms. A suggested explanation for this is that communal lands use the trees for firewood and run goats along with cattle, inhibiting the establishment of trees (Scholes 2003). Bush encroachment has been documented in East and Southern Africa (but not West Africa), South America (Uruguay/Argentina and Chile), North America (Texas, New Mexico) and Australia, but not in India, also a savanna environment. Furthermore, it did not happen simultaneously in those places, but 30-50 years after the widespread establishment of sedentary grazing management, what has been referred to as 'commercial' ranching above. This tends to disfavour the rising CO2 hypothesis, although rising CO2 may predispose the shift (Midgely and Bond 2001). In addition, bush encroachment tends to be an episodic phenomenon, where the tree cohorts can often be linked to issues in the ranching enterprise – such as drought-induced debt or downturns in the cattle price cycle (Scholes 2003, Wiegand et al 2006).

5. Impacts on ecosystems and human well-being

Woody encroachment brings a relatively rapid change, over a decade or two, from a highly productive grass layer to a sparse and unproductive grass component. Since cattle are grass-eaters, this change substantially reduces cattle productivity (Scholes 2003, Anderies *et al.*, 2004). Difficulties in mustering the cattle in dense bush are a contributing factor. Bush encroachment is expensive to reverse, since rapid results rely on arboricides or repeated mechanical or manual clearing. Therefore, wood encroachment leads to economic losses for cattle ranchers in what is frequently an economically-marginal occupation for a range of other reasons – distance to market, property sizes that are too small, and low commodity prices.

On the other hand, encroachment increases the supply of tree-based ecosystem services, such as wood for fuel, charcoal-making and building material. This is somewhat dependent on the species involved. The increase in woody cover could potentially also have macro and micro-climatic effects through impacts on albedo and CO_2 uptake, in addition to the decrease in methane emissions from cattle.

6. Management options for preventing or reversing regime shift

There is some agreement among researchers and extension workers that encroachment can be avoided by stocking lightly and burning frequently to prevent the establishment of trees and maintain grass crowns - the productive part of the grass that is less affected by fires (Janssen *et al.*, 2006; Roques *et al.,* 2001). This agreement is seldom reflected in management practice.

Attempts to reverse bush encroachment often have poor results, either due to the rapid resprouting of the trees or the conversion of the grass layer to less desirable species in the process . A common method involves the manual removal of woody vegetation, with repeated follow-up control and the use of fire to enhance the establishment and competitive advantage of grasses (Scholes 1985, Scholes 2003).

There are anecdotal reports of widespread mortality of the frequently near-dominant encroaching species after several decades, possibly related to disease, prolonged drought or simply old age, which provides windows for grass establishment and fuel load for intense fires.

7. Links to other regime shifts

None

8. Key direct drivers of the RS
    - 21.1. Habitat conversion or fragmentation
    - 21.2. Harvest and resource consumption
    - 21.3. External inputs (eg fertilizers, pest control, irrigation)
    - 21.4. Adoption of new technology (eg new fishing nets)
    - 21.5. Infrastructure development (eg roads, pipelines)
    - 21.6. Species introduction or removal
    - 21.7. Disease
    - 21.8. Soil erosion & land degradation
    - 21.9. Environmental shocks (eg fire, floods, droughts)
    - 21.10. Global climate change

22. Impacts on ecosystem services

22.1. Provisioning services
- Freshwater
- Food Crops
- Livestock
- Fisheries
- Wild animal and plant foods
- Timber
- Woodfuel
- Other crops (eg cotton)

22.2. Regulating services
- Air quality regulation
- Climate regulation
- Water purification
- Water regulation
- Regulation of soil erosion
- Pest & Disease regulation
- Pollination
- Natural hazard regulation

22.3. Cultural services
- Recreation
- Aesthetic values
- Knowledge and educational values
- Spiritual and religious

22.4. Biodiversity

23. Impacts on Key Ecosystem Processes

23.1. Soil formation
23.2. Photosynthesis
23.3. Primary production
23.4. Nutrient cycling
23.5. Water cycling

24. Impacts on Human Well-being

24.1. Food and nutrition
24.2. Health (eg toxins, disease)
24.3. Livelihoods and economic activity
24.4. Security of housing & infrastructure
24.5. Cultural, aesthetic and recreational values
24.6. Social conflict
24.7. No direct impact

25. Ecosystem type in which the RS occurs

25.1. Marine & coastal

25.2. Freshwater lakes & rivers
25.3. Temperate & Boreal Forests
25.4. Tropical Forests
25.5. Moist savannas & woodlands
25.6. Drylands & deserts (below ~500mm rainfall/year)
25.7. Grasslands
25.8. Tundra
25.9. Polar
25.10. Planetary

26. Land use under which the RS occurs
    26.1. Urban
    26.2. Small-scale subsistence crop cultivation
    26.3. Large-scale commercial crop cultivation
    26.4. Intensive livestock production (eg feedlots, dairies)
    26.5. Extensive livestock production (natural rangelands)
    26.6. Timber production
    26.7. Fisheries
    26.8. Mining
    26.9. Conservation
    26.10. Tourism
    26.11. Land use impacts are primarily off-site (e.g. dead zones in the ocean caused by fertilizer use in the continental interior; in these cases, also indicate the relevant land uses above)

27. Typical spatial scale at which RS occurs
    27.1. Local/landscape (e.g. lake, catchment, community)
    27.2. Sub-continental/regional (e.g. southern Africa, Amazon basin) (actual RS mechanism occurs at the regional scale OR cumulative impact/extent of local-scale RS is regional in scale)
    27.3. Global

28. Typical time scale over which RS occurs
    28.1. Weeks
    28.2. Months
    28.3. Years
    28.4. Decades
    28.5. Centuries
    28.6. Unknown

29. Reversibility of RS
  29.1. Irreversible (on 100 year time scale)
  29.2. Hysteretic
  29.3. Readily reversible
  29.4. Unknown

30. Confidence: Existence of RS
  18.1. Speculative – Regime shift has been proposed, but little evidence as yet
  18.2. Contested – Reasonable evidence both for and against the existence of RS
  18.3. Well established – Wide agreement in the literature that the RS exists

19. Confidence: Mechanism underlying RS
  19.1. Speculative – Mechanism has been proposed, but little evidence as yet
  19.2. Contested – Multiple proposed mechanisms, reasonable evidence both for and against different mechanisms
  19.3. Well established – Wide agreement on the underlying mechanism

20. Evidence
  20.1. Models
  20.2. Paleo-observation
  20.3. Contemporary observations
  20.4. Experiments
  20.5. Other

21. Contributors

Juan Carlos Rocha
Stockholm Resilience Centre
juancarlosrochag@gmail.com

Oonsie Biggs
Stockholm Resilience Centre

Bob Scholes
Council for Scientific and Industrial Research, South Africa

22. Last updated
February 15, 2010

23. Key References

Anderies, J.M.; Janssen, M.A; ans Walker, B. 2002. Grazing management, resilience, and the dynamics of a fire-driven rangeland system. Ecosystems 5 (1): 23-44.

Dublin, H. T., Sinclair, A. R. and McGlade, J. (1990). Elephants and fire as causes of multiple stable states in the Serengeti-Mara woodlands. Journal of Animal Ecology 59, 1147-1164.

Higgins S. I., W. J. Bond, and W. S. W. Trollope. 2000. Fire, resprouting and variability: a recipe for grass-tree coexistence in savanna. Journal of Ecology, 88:213-229.

Janssen, M.A; Anderies, J.M; and Walker, B. 2004. Robust strategies for managing rangelands with multiple stable attractors. Journal of Environmental Economics and Management

Midgley, J. J. and Bond, W. J. (2001). A synthesis of the demography of African acacias. Journal of Tropical Ecology 17, 871-886.

Noy-Meir, I. (1982). Stability of plant-herbivore models and possible applications to savanna. In: Ecology of Tropical Savannas (Huntley, B. J. and Walker, B. H. ed.), pp.591-609. Berlin: Springer.

Poynton, R.J. 1990. The genus Prosopis in South Africa. S. Afr. For. J. 152: 62–66.

Rietkerk, M., Dekker, S. C., de Ruiter, P. C. and van de Koppel, J. (2004). Self-organized patchiness and catastrophic shifts in ecosystems. Science 305, 1926-1929.

Roques, K.G; O'Connor, T.G; Watkinson, A.R. 2001. Dynamics of shrub encroachment in an African savanna: relative influences of fire, herbivory, rainfall and density dependence. J Appl Ecol 38 (2): 268-280

Scheffer, M., Carpenter, S. R., Foley, J. A., Folke, C. and Walker, B. H. (2001). Catastrophic shifts in ecosystems. Nature 413, 591-596.

Scholes R.J. 1985. A Guide to Bush Clearing in the Eastern Transvaal Lowveld. Occasional Report of the Resource Ecology Group, University of the Witwatersrand. 50 pp.

Scholes, RJ & S. Archer. 1997. Tree-grass interactions in savannas. Annual Review of Ecology and Systematics 28, 517-44.

Scholes R. J. 2003. Convex Relationships in Ecosystems Containing Mixtures of Trees and Grass. Environmental and Resource Economics, 26:559-574.

Staver A. C., W. J. Bond, W. D. Stock, S. J. van Rensburg, and M. S. Waldram. 2009. Browsing and fire interact to suppress tree density in an African savanna. Ecological Applications, 19:1909-1919.

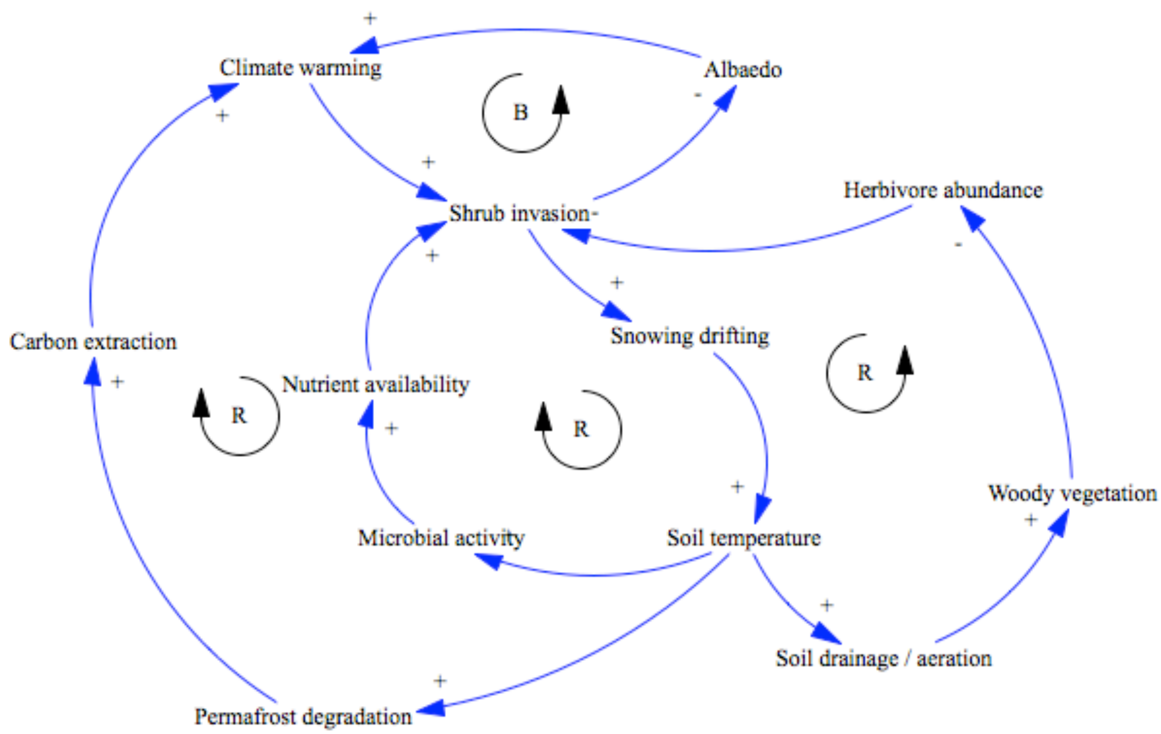
van de Koppel, J. and Rietkerk, M. 2000. Herbivore regulation and irreversible vegetation change in semi-arid grazing systems. Oikos 90 (2): 253-260

Walker, B.H. 1993. Rangeland ecology: understanding and managing change. Ambio 22: 2-3.

Wiegand, K; Saitz, D; and Ward, D. 2006. A patch-dynamics approach to savanna dynamics and woody plant encroachment - Insights from an arid savanna. Perspect Plant Ecol 7 (4): 229-242

Shrub invasion: Arctic Tundra changing towards Boreal forest

1. Diagrams/Photos of regime shift dynamics



2. Summary

The driver behind the changes in Arctic tundra towards boreal forest regime has been the increasingly warming climate due to high concentrations of carbon in atmosphere from anthropogenic activity allowing the shrub abundance as a pioneer species for boreal forest to increase in a significant amount. This regime shift to boreal forest with spruce and pine as the dominant species will unlikely occur in this century due to time lags involved with specie migration. Thus shrub expansion over Arctic tundra regions is the first indicator of this regime shift which is enforced by C release in atmosphere due to permafrost degradation therefore increasing climate warming and increasingly occurring microbial activity thereby providing shrubs with nutrients. Sufficient amount of herbivores in tundra has had impact on shrub expansion in a limiting way thus having a potential to maintain the shrub domination phase on a long term basis.

3. Description of the alternate regimes and reinforcing feedbacks

This regime shift encompasses extended change in Arctic tundra biodiversity and soil structure due to increased climate warming. Thus far shrub invasion has been the main variable which has led to suggestions of potential regime shift. The two highlighted alternative regimes are:

Arctic tundra. This regime is characterized by low atmospheric temperatures that enable to form a layer of permanently frozen subsoil (permafrost) consisting mostly of gravel and finer material (UCMP). It determines that ecosystems have low rates of primary production due to impeded mineral nutrient cycling. Short growing season in summer influence the vegetation and its root systems by limiting their vertical expansion therefore only plant species (lichens, liverworts, mosses) that are adapted to snow sweeping winds and disturbances of the soil can survive in these circumstances (UCMP). The atmospheric cold and difficult conditions for plant growth ensures the feedback to maintain this regime.

Boreal forest. Ecosystems in this regime are characterized by Flora that consist mostly of cold-tolerant evergreen conifers, such as the evergreen spruce (Picea), fir (Abies), and pine (Pinus), and the deciduous larch or tamarack (Larix). Before these species are established in a region, there is an increased canopy component of early-successional species such as aspen and paper birch (Frelich 1995). Shrubs act as the pioneer species that establish in a territory before trees are able overcome and consolidate there. This change can occur in a long time period varying from several decades to centuries based on the time lag for each species to migrate and the favorable conditions in the specific ecosystem. Due to Arctic warming and continuingly increasing growing season the shrub species have expanded throughout the Arctic tundra increasing their abundance in the form of patches. The shrub and tree species established above the snow has been considered of having an impact on seasonal and annual land surface energy exchange, primarily by masking the high albedo of snow and also through partitioning of net radiation into sensible and latent heat in summer months thus warming the climate even further (Bonan et al. 1995).

As drifting snow is common in tundra, the deep drifts often surround and extend downwind from these shrub patches thereby trapping and holding the snow, thus increasing the insulation of soil (Sturm 2005). This promotes the increase of soil temperature allowing for microbial activity to remain active during the frigid arctic winter, producing enough critical nutrients – particularly nitrogen that stimulates shrub growth, to utilize the following summer and increase their abundance (Chapin III 2005). These changes create feedbacks that alter both the structure and the function of ecosystems (Myers-Smith 2007). Considering the fact that soil temperature increases under the snow it leads to permafrost degradation. In addition, thawing of permafrost could release the trapped carbon from tundra soils contributing to climate warming thus increasingly accelerating the rate of carbon release (Walter et al) which already has been projected as a part of the annual estimate of the Arctic carbon budget (Fahnestock 2000). Changes in this variable can also be associated with dramatic changes in below-ground conditions for plant growth (Loyd 2003) creating areas of improved drainage as due to improved vertical flows of water through the soil (Woo et al., 1992). That plays a significant role of tall woody vegetation to

successfully establish in level terrain underlain by permafrost as they are dependent on well-drained soils in order to expand in the tundra (Loyd 2003).
The herbivores like reindeers and microtine rodents can be influenced by the change towards increasingly expanding woody vegetation as they prefer lichens, dwarf shrubs graminoids and deciduous shrubs over tall woody shrubs (Sturm 2005). This means that in the case of increased continuity of this trend, it can result in various tundra specie distinctions or radical decrease in numbers. In general reindeers can preserve open heathlands by inhibiting the expansion of shrubs and trees (Olofsson 2009). This suggests that it can be a possibility for the shrub domination to last in a longer time period without the expansion of successional boreal forest species – burch, aspen etc.

4. Drivers that precipitate the regime shift

The main driver of this regime shift is climate warming leading to changes in composition and abundance of arctic plants, livelihood of animals and soil structure (Olofsson 2009). Anthropogenic activities that cause carbon emissions in atmosphere are mainly behind this initial disturbance. Continuingly increasing carbon release from both anthropogenic and natural sources (due to permafrost degradation) to atmosphere will continue to initiate the climate warming and cause more rapid expansion of boreal forest than at the moment. The increase of soil temperature can be seen as a fast variable in this new regime that immediately responds to shrub caused snow drifts. The trigger variable for the regime to evolve is shrubs and their expansion as they are a vital link for the boreal forest tree line expansion further north and shrubs closely relate to other variables in the feedback mechanisms. However by the slow variable category can be mentioned the permafrost degradation which result in carbon release. Response time can be context dependent, though Zimov et al. (2006) suggest that most carbon in by only recently thawed yedoma (windblown dust) will be released within a century.

5. Impacts on ecosystems and human well-being

Terrestrial vegetation will undergo large geographic changes throughout the tundra zone losing its natural biodiversity and landscape (Bonan 1992). This will decrease the distribution of obligate tundra species such as hoary marmot (Marmota caligata), collared pika (Ochotona collaris), and ptarmigan (Lagopus sp.) (Martin as cited in Mayers-Smith 2007). Changes in vegetation are also likely to affect composition of foraging mammals and birds (Hinzman et al., 2005). In addition to modifying wildlife habitat, by increased woody shrub species and their height and density will make traversing tundra more difficult, forcing the caribou to migrate to where they graze and that would also be a problem for subsistence hunters and the communities that rely on caribou for food as well as hikers. Change in regulating ecosystem services from being carbon sinks to becoming a source from Arctic permafrost thawing is a major concern for the ecosystems and human well-being in the future. However a new service will appear – timber harvesting due to wide scale tree expansion in the Arctic tundra regions.

6. Management options for preventing or reversing regime shift

In order to prevent/reverse this regime shift it is a necessity to manage the input of carbon in atmosphere in order to prevent the increase on climate warming even more in a distant future. The suggestion of planetary boundaries for CO_2 level of 350 ppm is the first step in the direction of doing that (Rokstrom et al. 2009). Increased understanding of the influence of climate change on the complexity of arctic systems has to be in place and will be essential for the adaptation of human social, economic, and cultural systems to the changes taking place in the Arctic.(hinzman 2005). A potential discussion can be predicted in the future concerning the desirable management strategy and its outcome as there will be potentially stakeholders involved who will see this regime shift as desirable and beneficial (timber production, game hunting etc.).

7. Links to other regime shifts

8. Key direct drivers of the RS

- 9.1 Vegetation conversion and habitat fragmentation
- 9.2 Harvest and resource consumption
- 9.3 External inputs (eg fertilizers, pest control, irrigation)
- 9.4 Adoption of new technology (eg new fishing nets)
- 9.5 Infrastructure development (eg roads, pipelines)
- 9.6 Species introduction or removal
- 9.7 Disease
- 9.8 Soil erosion & land degradation
- 9.9 Environmental shocks (eg fire, floods, droughts)
- 9.10 Global climate change

10. Impacts on ecosystem services

- 10.1 Provisioning services
  - Freshwater
  - Food Crops
  - Livestock
  - Fisheries
  - Wild animal and plant foods
  - Timber
  - Woodfuel
  - Other crops (eg cotton)
- 10.2 Regulating services
  - Air quality regulation
  - Climate regulation
  - Water purification
  - Water regulation
  - Regulation of soil erosion
  - Pest & Disease regulation
  - Pollination

Natural hazard regulation

10.3 Cultural services

Recreation

Aesthetic values

Knowledge and educational values

Spiritual and religious

10.4 Biodiversity

11. **Impacts on Key Ecosystem Processes**
    - 11.1 Soil formation
    - 11.2 Photosynthesis
    - 11.3 Primary production
    - 11.4 Nutrient cycling
    - 11.5 Water cycling

12. **Impacts on Human Well-being**
    - 12.1 Food and nutrition
    - 12.2 Health (eg toxins, disease)
    - 12.3 Livelihoods and economic activity
    - 12.4 Security of housing & infrastructure
    - 12.5 Cultural, aesthetic and recreational values
    - 12.6 Social conflict
    - 12.7 No direct impact

13. **Ecosystem type in which the RS occurs**
    - 13.1. Marine & coastal
    - 13.2. Freshwater lakes & rivers
    - 13.3. Temperate & Boreal Forests
    - 13.4. Tropical Forests
    - 13.5. Moist savannas & woodlands
    - 13.6. Drylands & deserts (below ~500mm rainfall/year)
    - 13.7. Grasslands
    - 13.8. Tundra
    - 13.9. Polar
    - 13.10. Planetary

14. **Land use under which the RS occurs**
    - 14.1. Urban
    - 14.2. Small-scale subsistence crop cultivation
    - 14.3. Large-scale commercial crop cultivation
    - 14.4. Intensive livestock production (eg feedlots, dairies)
    - 14.5. Extensive livestock production (natural rangelands)
    - 14.6. Timber production

14.7. Fisheries
14.8. Mining
14.9. Conservation
14.10. Tourism
14.11. Land use impacts are primarily off-site (e.g. dead zones in the ocean caused by fertilizer use in the continental interior; in these cases, also indicate the relevant land uses above)

15. **Typical spatial scale at which RS occurs**
    15.12. Local/landscape (e.g. lake, catchment, community)
    15.13. Sub-continental/regional (e.g. southern Africa, Amazon basin) (actual RS mechanism occurs at the regional scale OR cumulative impact/extent of local-scale RS is regional in scale)
    15.14. Global

16. **Typical time scale over which RS occurs**
    16.1. Weeks
    16.2. Months
    16.3. Years
    16.4. Decades
    16.5. Centuries
    16.6. Unknown

17. **Reversibility of RS**
    17.1. Irreversible (on 100 year time scale)
    17.2. Hysteretic
    17.3. Readily reversible
    17.4. Unknown

18. **Confidence: Existence of RS**
    18.1. Speculative – Regime shift has been proposed, but little evidence as yet
    18.2. Contested – Reasonable evidence both for and against the existence of RS
    18.3. Well established – Wide agreement in the literature that the RS exists

19. **Confidence: Mechanism underlying RS**
    19.1. Speculative – Mechanism has been proposed, but little evidence as yet
    19.2. Contested – Multiple proposed mechanisms, reasonable evidence both for and against different mechanisms
    19.3. Well established – Wide agreement on the underlying mechanism

20. **Evidence**

20.1. Models
20.2. Paleo-observation
20.3. Contemporary observations
20.4. Experiments
20.5. Other

21. **Contributors**

22. **Key References**

Bonan, G. B., D. Pollard, and S. L. Thompson. 1992. Effects of Boreal Forest Vegetation on Global Climate. *Nature* 359: 716-18

Frelich, L.E., and P.B. Reich. 1995. Spatial patterns and succession in a Minnesota southern boreal forest. *Ecological Monographs* 65(3): 325-346

Hinzman, L. D., et al. 2005. Evidence and Implications of Recent Climate Change in Northern Alaska and Other Arctic Regions. *Climatic Change* 72(3)

Lloyd A. H., 2003. Effects of Permafrost Degradation on Woody Vegetation at Arctic Treeline on the Seward Peninsula, Alaska, *Permafrost Periglac. Process.* 14: 93–101

Myers-Smith I. (2007), Shrub line advance in alpine tundra of the Kluane Region: mechanisms of expansion and ecosystem impacts, *Arctic*. 60(4): 447-451
Oechel, W.C., S. J. Hastings, G. Vourlitis, M. Jenkins, G. Riechers & N. Grulke. 1993. Recent change of Arctic tundra ecosystems from a net carbon dioxide sink to a source. *Nature*, 361: 520-523

Olofsson, J., L. Oksanen, T. Callaghan, P.E. Hulme, T. Oksanen and O. Suominen. 2009. Herbivores inhibit climate-driven shrub expansion on the tundra *Global Change Biology* 15(11): 2681 – 2693

Rockström, J., et al. 2009. Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society* 14(2):32

Sturm, M., J. Schimel, G. Michaelson, J.M. Welker, S.F. Oberbauer, G.E. Liston, J. Fahnestock, and V.E. Romanovsky. 2005. Winter biological processes could help convert arctic tundra to shrubland. *Bioscience* 55(1): 17-26

UCMP: The tundra biome. University of California Museum of Paleontology. http://www.ucmp.berkeley.edu/exhibits/biomes/tundra.php Last visited: 26 Jan. 2010

Welker, J.M., J.T Fahnestock. M.H.Jones. 2000, Annual CO, flux from dry and moist arctic tundra: Field responses to increases in summer temperature and winter snow depth. *Climatic Change* 44(1-2): 139-150.

Zimov, S. A., E.A.G. Schuur., S. F. Chapin III. 2006. Permafrost and the Global Carbon Budget. *Science* 312(16): 1612-1613